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Film Transfer in Helium II:
I—The Thermo-Mechanical Effect

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ABSTRACT. The existence of a thermo-mechanical pressure difference has been established with the transfer film instead of a capillary connecting the two volumes of liquid helium II. It is shown that under these circumstances reversible conditions are closely approximated since return flow of heat or liquid through the film is negligible. The speed with which a thermo-mechanical pressure difference can be established is limited by the same critical transfer rate as that determining film transport under gravitation.

§ 1. INTRODUCTION

In a number of experiments (Daunt and Mendelssohn 1939 a) the transport of helium II along a film covering all solid surfaces in contact with the liquid and the properties of this film have been systematically investigated. The present series of papers presents a report on further observations made on these phenomena carried out since. The work described deals with various aspects of the *flow* properties of the film only, and such experiments as have been carried out on the static properties of the film (cf. Brown and Mendelssohn 1947) will be published separately.

All the experiments reported in this series have been made in a number of identical cryostats of the kind described by us recently (Daunt and Mendelssohn 1948). These apparatuses, combining a small Linde liquefier with a helium cryostat for direct visual observation, have proved of considerable value in this type of research. They combine simplicity and reliability of operation with very small heat influx into the experimental arrangement, which is of particular value in observations on the film. The high degree of purity of the liquefied helium which is an essential feature of these liquefier-cryostats prevents, as will be shown in the third paper of this series, the occurrence of spurious effects which have proved troublesome in similar investigations made with the conventional type of helium cryostat.

In their attempts at measuring the heat conduction of liquid helium II, Allen, Peierls and Uddin (1937) noticed that their observations were disturbed by a peculiar flow of liquid which occurred in the opposite direction to the flow of heat. This thermo-mechanical effect (Allen and Jones 1938), which has sometimes been called the 'fountain phenomenon', presents in the actual observation a somewhat complex character and can be interpreted better if we consider the following simplified idealized arrangement, diagrammatically shown in Figure 1. Here two perfectly isolated volumes of liquid helium II, A and B, are connected through the capillary C, the whole having initially the one temperature, T. If a quantity of heat Q is applied at B, its temperature rises to T_1 and at the same time a flow of liquid takes place through the capillary from A to B. Consequently, the level of A drops and that of B rises, and mechanical work is done. If we make the assumption that the system is a reversibly working heat engine, the maximum work which can be done by it is

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$$W = Q(T_1 - T)/T_1 \qquad \ldots\ldots(1)$$

and is represented by the level difference between A and B. This means that, once a given amount of heat has been supplied, a certain difference in level should be effected and maintained, provided that the capillary acts as a non-return valve. In practice, however, there are a number of sources of energy dissipation. Heat is lost from B by the thermal conductivity of the arrangement to its surroundings and by evaporation; moreover a return flow through C takes place. The observations of Allen and Reekie (1939), Kapitza (1941), Keesom and Duyckaerts (1947), Mellink (1947) and Meyer and Mellink (1947), in which a constant heat supply into B produced a constant difference in level, represent a *dynamic* equilibrium in which the work done continually by the thermo-mechanical effect is balanced by a steady flow of energy out of B. It is clear that, while it may be possible to calculate the other sources of energy dissipation in the system, an assessment of the energy loss along the capillary must remain impossible so long as we have no satisfactory theory of the heat conductivity in liquid helium II. A further study of the phenomenon had therefore to aim at an elimination of this complex return flow.

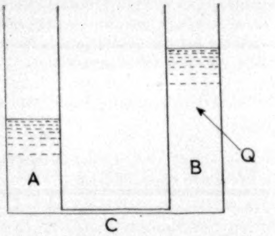

Figure 1. The thermo-mechanical effect.

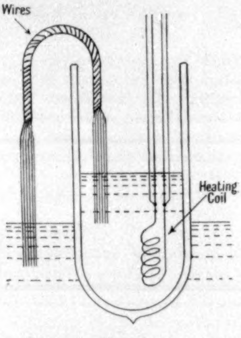

Figure 2. Transfer vessel.

Our experiments on the transfer of helium II through a surface film above the liquid level (Daunt and Mendelssohn 1939 a) had revealed a close resemblance between the flow phenomena in this film and those observed in capillaries

(Allen and Misener 1939). It was therefore of interest to see whether a thermo-mechanical effect would also occur if the two volumes of helium were connected by a surface film instead of a capillary. As has already been briefly reported (Daunt and Mendelssohn 1939 b), this has actually been found to be the case, and the present paper gives a full account of the experiments* carried out and the conclusions which can be drawn from them with regard to the nature of the thermo-mechanical effect.

§ 2. EXPERIMENTAL ARRANGEMENT

A small Dewar vessel (Figure 2) whose internal length was 7·2 cm. and internal diameter 3·34 mm. was suspended in the cryostat from a winch so that it could be raised or lowered in the bath of liquid helium II. The inside of the vessel was graduated and the positions of the levels of the liquid both inside and outside were observed with a long focus microscope. The level differences could be read to an accuracy of 0·03 mm. Inside the vessel a small heating coil was fixed, current and potential leads being attached thereto so that the energy supplied to the liquid inside could be determined. In order to obtain a larger effect the connecting surface between the helium inside and that outside the vessel was increased by a bundle of fine copper wires folded over its edge; 103 bare copper wires of 40 s.w.g. were used. We have observed previously that the transfer of liquid along drawn wires might be larger than calculated on the assumption of a smooth surface. The width of the connecting surface was therefore determined directly by measuring the transfer from the raised beaker when the flow was allowed to take place isothermally and comparing the result with our earlier observations. It was found by this method that the effective width of the connecting surface (including the glass vessel) was 8·5 cm., in good agreement with the geometrical surface.

The vapour pressure of the bath was measured with a butylphthalate manometer and the temperature kept constant to less than 0·003 degree.

§ 3. RESULTS

When no heat was supplied to the heating coil the levels of the helium inside and outside the vessel were found, in accordance with our previous observations, to adjust themselves to equal height. On supplying heat, the liquid inside the vessel rose and maintained a steady difference in level between it and the helium outside. These level differences Δh are plotted against heat input $\dot{Q}$ for three different temperatures in Figure 3. All the points plotted in the figure are the mean of two or more separate observations. Owing to the small differences in level occurring at 2·05° K., the accuracy of these measurements is inferior to those at the two lower temperatures.

The results at 1·32° K. and 1·71° K. show that Δh rose with increasing heat input, reached a maximum and then decreased with further increase in $\dot{Q}$. If the heating was increased beyond a certain critical value $\dot{Q}_c$ it was found that the effect was destroyed and the helium inside evaporated away faster than it was transferred into the vessel. An exact experimental determination of this critical heating $\dot{Q}_c$ was very difficult. However, if more heat than $\dot{Q}_c$ was supplied it was observed that the level inside failed to maintain an equilibrium value, but dropped gradually and continuously below the outer level, as one would expect for an evaporative process. One can therefore indicate the limits between which this critical heat input must lie at each temperature. These limits are set out in the Table. The values $\dot{Q}_1$ give the highest values of $\dot{Q}$ for which an equilibrium difference in level was obtained and observed, and the value $\dot{Q}_2$ are the lowest values of $\dot{Q}$ at which the effect was observed to be destroyed.

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* These experiments were performed in 1939 and their publication was delayed owing to the war.

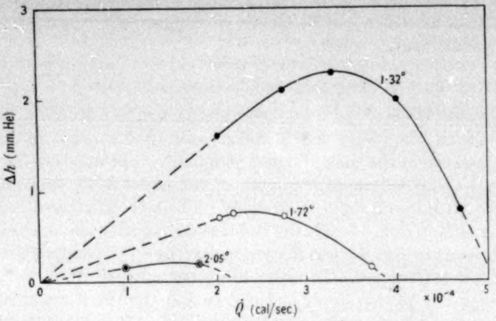

Figure 3. Thermo-mechanical effect in the transfer film in dependence on head input.

T(°K.)	$\dot{Q}_1(<\dot{Q}_c)$ (cal/sec.)	$\dot{Q}_2(>\dot{Q}_c)$ (cal/sec.)	$\dot{Q}_c$ (calc.)
1·32	$4{\cdot}6 \times 10^{-4}$	$5{\cdot}6 \times 10^{-4}$	$4{\cdot}9 \times 10^{-4}$
1·71	$3{\cdot}75 \times 10^{-4}$	$4{\cdot}6 \times 10^{-4}$	$4{\cdot}2 \times 10^{-4}$
2·05	$1{\cdot}8 \times 10^{-4}$	$2{\cdot}8 \times 10^{-4}$	$1{\cdot}4 \times 10^{-4}$

§ 4. DISCUSSION

These experiments show that, similar to the phenomena at the ends of a capillary, a thermo-mechanical effect occurs if the two volumes of liquid are joined by a surface film. They also show that with a steady heat supply we arrive at a stationary level difference denoting a dynamical equilibrium in which all the heat supplied to the inside of the vessel is dissipated. However, in contradistinction to the experiments using capillaries or powder-filled tubes, the sources of energy dissipation can be assessed with fair accuracy in observations on films. Our previous experiments have demonstrated that there exists no viscous flow in the film and that its heat conduction is negligible, which means that, in contradistinction to the case of a capillary, there is no energy dissipation along the connecting link between the two volumes of helium. The heat fed into the vessel is therefore used only (*a*) to evaporate liquid and (*b*) in supplying energy which may be required for taking helium atoms out of the film into the bulk liquid. It is clearly this latter term, which appears like a ' heat of excitation ', which is responsible for the appearance of the thermo-mechanical effect. This energy is equal to $T\Delta S$, where T is the temperature of the helium in the vessel and ΔS the change in entropy suffered by the helium when taken from the film into the bulk liquid. The total heat supplied per unit time $\dot{Q}$ is therefore equal to

$$\dot{Q} = nr(L + T\Delta S), \qquad \ldots\ldots(2)$$

where n is the width in centimetres of the connecting film, r the number of grammes of liquid helium transported for each centimetre width of the film, and L the latent heat of evaporation of the bulk liquid.

At any fixed temperature, therefore, we may conclude that r is directly proportional to $\dot{Q}$ as long as we observe a state of equilibrium, i.e. a constant level difference. The experiments show, however, that at each temperature when a certain heat input $\dot{Q}_c$ is exceeded, such a constant level difference cannot be maintained any more, which means that more helium is evaporated than can be furnished by transfer along the film. The existence of such limiting values of $\dot{Q}$ is actually shown by our experiments.*

A quantitative evaluation of $\dot{Q}_c$ can be made from equation (2). Although the exact value of ΔS is undetermined, its maximum value clearly cannot be greater than the *total* entropy of liquid helium II at the same temperature. Even taking this maximum value for ΔS, the term $T\Delta S$ is very small compared with L except, possibly, near the λ-point, and consequently the value of $\dot{Q}_c$ for temperatures below about 1·9° K. can be calculated without more than 5% error, by neglecting $T\Delta S$. The question arises as to what value should be used for r. The fact that critical values for $\dot{Q}$ are observed immediately suggests the existence of a critical flow rate. We therefore set r equal to ρR, where ρ is the density of the liquid and R the critical transfer rate (measured in cm³/sec. per cm. width of the connecting film) which had been observed in our isothermal flow experiments. The values of $\dot{Q}_c$ calculated in this way from equation (2) are tabulated in the last column of the Table. It will be seen that these calculated values are in good agreement with the observed values of the limits of the value of $\dot{Q}_c$ also given in the Table. The agreement for the temperature of 2·05° K. is not quite so good as for the two lower temperatures, but it can be accepted as giving support for the mechanism of the effect assumed above.

The differences of pressure and temperature occurring in the thermo-mechanical effect have been thermodynamically correlated with the heat input by H. London (1939). Considering the circulation of helium both through the liquid and vapour phase as outlined above, and assuming its reversibility, we obtain in our case,

$$T\left(\frac{\Delta p}{\Delta T}\right)_{\Delta T\to 0} = \rho(L + T\Delta S), \qquad \ldots\ldots(3)$$

where ρ is the density of the liquid, Δp the difference in hydrostatic pressure between the inner and outer containers and ΔT the difference in temperature between them.

If, as seems reasonable from the results of other experiments, we assume that the mechanical resistance offered to the flow of helium along the film is zero, we must conclude that the major portion of the resistance to the circulation of matter occurs in the return flow of helium vapour. This will depend on the geometry of the vessels and on the viscosity of the vapour. The pressure available to overcome this resistance is provided by the difference in vapour pressure between the helium in the vessel and that of the bath and by the difference in hypsometric pressure. As the latter is in general negligible compared with the vapour pressure difference,† we may write for laminar flow that nr, the total flow of helium, is given by

$$nr = \frac{\rho' G}{\eta}(\Delta \Pi), \qquad \ldots\ldots(4)$$

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* Such critical values for $\dot{Q}$ have also been observed by Kikoin and Lazarew (1938) in experiments of a somewhat different character.

† In the experimental arrangement described here, by neglecting the hypsometric pressure we introduce an error of only about 4%.

where η is the viscosity of the vapour, G a term involving the geometry of vessel only,* ρ' the vapour density and $\Delta\Pi$ the difference in vapour pressure.

If we consider small values of heat input $\Delta\dot{Q}$ only, so that we may neglect any kinetic energy terms, we get from (2) and (4)

$$\Delta\dot{Q} = \frac{\rho' G}{\eta}(T\Delta S + L)\frac{d\Pi}{dT}\Delta T, \qquad \ldots\ldots(5)$$

where $(d\Pi/dT)$ is the slope of the vapour pressure curve at the temperature concerned.

This will give a measure of the heat conductivity of the arrangement for small heat inputs. It will be seen that the value of $\Delta\dot{Q}$ is dependent on the geometrical form of the apparatus used in its measurement in such a way that a straight derivation of heat conductivity cannot be made (the term G depending on the fourth power of the diameter of the vapour outlet). For small heat inputs, however, $\Delta\dot{Q}$ should be proportional to ΔT.

A check on the above calculations can be made if we combine equations (3) and (5) to obtain

$$\left(\frac{\Delta p}{\Delta\dot{Q}}\right)_{\dot{Q}\to 0} = \frac{\rho\eta}{\rho' TG}\Big/\left(\frac{d\Pi}{dT}\right) \qquad \ldots\ldots(6)$$

where the various terms on the right-hand side have the significance already described. Calculations have been made, the values of η being taken from van Itterbeek and Keesom (1938) and those for ρ' having been computed by means of the Clausius–Clapeyron equation from known values of the latent heat and also from extrapolation of the results obtained by Keesom and Kraak (1935). The probable error for the calculated values of ρ' is about 10%. In Figure 4 the calculated values of $(\Delta p/\Delta\dot{Q})_{\Delta\dot{Q}\to 0}$ obtained in this way are shown by the full curve, and the observed results are given by the circled points.

The agreement evidenced by Figure 4 between the theory and experiment, in view of the possible experimental errors, is satisfactory, and indicates that our assessment of the mechanism of the thermo-mechanical effect using films as connecting link is most probably correct. It also indicates that little or no viscous return flow takes place through the film.

§ 5. CONCLUSIONS

The observations described in this paper lead to two conclusions which not only seem of interest for an interpretation of the film transfer but also appear significant quite generally for the transport phenomena in liquid helium II. Firstly, the fact emerges that film transfer under a thermal potential is also limited by a critical flow rate, and that this rate is identical with the critical flow observed previously by us under gravitational potential. Our experiment on the heat conductivity of the film (Daunt and Mendelssohn 1939 a) had already given an indication that this may be so, but it was doubtful whether in these observations an actual temperature difference at the end of the film had occurred. More likely, the heat transport in that case was isothermal. In the present measurements, on the other hand, a thermo-mechanical pressure difference is established which must be accompanied by a difference in temperature between the two volumes of liquid. The data given in Figure 3 indicate how increases in heat input produce proportional increases in the transfer rate until at a certain value of Q_c, i.e. at a critical flow rate, this process breaks down. The appearance of the *same* critical rate, irrespective of whether the flow is initiated by a gravitational or a thermal potential, makes it clear that the existence of a limiting velocity must be an essential property of the phenomenon of superflow. In the case of film transfer this limitation appears clear and unambiguous in the observations. The phenomenon in channels filled with bulk liquid is evidently more complex, but various experiments (Kapitza 1941, Meyer and Mellink 1947, Bowers and Mendelssohn 1950) also provide ample evidence of a breakdown of superflow when a critical velocity is exceeded.

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* G is given by Poiseuille's formula for the flow of a compressible fluid, if the flow is laminar. The formula (4) is an approximation to this, valid when $\Delta\Pi$ is small, and is legitimate for the experimental arrangement described in this paper. The value of G calculated for this arrangement, in which the wicks were situated along the axis of the vessel, is $2{\cdot}8 \times 10^{-6}$ C.G.S. units. The formula (4) will fail if the flow of vapour becomes turbulent. This occurs, however, at relatively high velocities (cf. van Itterbeek and Keesom 1938), which would only take place in vessels with very constricted vapour outlets. For our apparatus the returning vapour had a maximum velocity of the order of 20 cm/sec., for which the flow should be laminar.

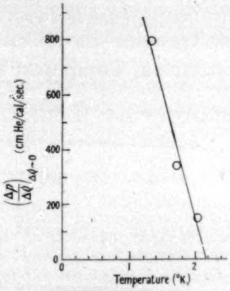

Figure 4.

The second conclusion concerns the mechanism of superflow under a temperature gradient. Interpretation of the thermo-mechanical effect on the basis of a two-fluid model (cf. Tisza 1938) has made use of a counter-flow in opposite directions of (*a*) the normal fluid and (*b*) the superfluid, which has been likened to an osmotic diffusion. In this way it has been assumed that the temperature difference between A and B (Figure 1) produces an osmotic pressure in the normal fluid which in turn must give rise to superflow if the density in a closed system containing the fluid is to remain constant. Thus if, as is usually assumed, the superfluid component has no initial momentum, normal flow has to be invoked as the primary cause for the thermo-mechanical effect. The occurrence of this effect with the film in the place of the connecting link C is therefore of special interest. The film phenomena in general give no evidence for the existence of normal viscous flow, and this fact is emphasized by the validity of equation (6) as demonstrated in Figure 4. This means that if one wishes to retain the two-fluid concept, it is necessary to ascribe momentum to the superfluid. Our results show that the superfluid constituent must be capable of equalizing differences in concentration, i.e. temperature, within the liquid as a whole by primary action and not merely in the form of a compensating flow to a re-distribution of the normal component.

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Film Transfer in Helium II: II—Influence of Geometrical Form and Temperature Gradient

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ABSTRACT. Experiments have been carried out in order to investigate a possible dependence of the film transfer in liquid helium II on the geometrical conditions of the measuring arrangement or on a temperature gradient along the film. Using transfer vessels of different shape, no variation in the rate of transfer could be detected. Equally no change from the ordinary rate of flow could be found under temperature differences up to $3{\cdot}5\times10^{-2}$ deg.

§1. INTRODUCTION

The earlier experiments, as well as those described in the preceding paper (Daunt and Mendelssohn 1950), all emphasize the invariance, at a given temperature, of the rate of transfer along the helium film. It was therefore surprising when in the course of experiments to isolate the helium film from the bulk liquid (Brown and Mendelssohn 1947) it was found that on occasion somewhat higher flow rates would occur. In all cases where such high rates were observed they appeared to be associated with film transport through small orifices about one millimetre in diameter. In the experiments of Daunt and Mendelssohn (1939 a) it had been established that the flow rate in and out of a beaker with a constriction was strictly proportional to the perimeter of the latter. However, the present experimental arrangement, that of a hole in a diaphragm, seemed to present a sufficiently different geometrical condition to merit further investigation. Experiments were therefore carried out in the conventional manner with a number of glass vessels by suspending them partly immersed in liquid helium II and measuring the in-and-out flow. The common feature of all these vessels was that they were completely closed except for a small aperture punched into the glass wall. The sizes of the apertures ranged from 0·5 to 3 mm. and the size of the vessel, as well as the shape, was varied, allowing different ratios of solid wall to liquid content.

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Systematic observations on vessels with various combinations of the above-mentioned characteristics yielded, however, no consistent results. High rates would on occasion be observed, the rate varying in some cases with the height of the aperture above the liquid level, but not in others. Moreover, with the same vessel high flow rates would occur in one particular experiment but not in a subsequent one, and vice versa. It thus became clear that we had failed to establish the essential physical condition for producing high rates of film transport. On the whole it appeared that increased flow rates would occur fairly rarely and only when the film passed through a small aperture; an ordinary beaker investigated under the same conditions would *always* exhibit the normal flow rate.

While these experiments were in progress a paper by Atkins (1948) was published in which he announced the consistent observation of very high transport rates. In particular he described two experimental arrangements, one of them yielding rates of more than *ten* times the normal ones, while the ‘ high ’ rates observed by us in flow through apertures were never much more than twice the normal. In view of our previous inability to obtain consistently high flow rates, and because some of Atkins' observations seemed to be in contradiction to our earlier experiments, it was decided to repeat and, if possible, to amplify his work.

§ 2. EFFECTS OF GEOMETRICAL FORM

Atkins' first set of observations was to some extent similar to our experiments mentioned above because they were made on vessels of a particular shape. He had used glass capillaries ending in bulbs and had found that in contradistinction to the results of Daunt and Mendelssohn the transport rate was not only much higher but also *varied* strongly over the length of the capillary. He concluded that this variation was a function of the distance between the top rim of the capillary and the higher of the two liquid levels; the smaller the height of the film above the bulk liquid the higher was the transport rate.

In conjunction with our work on film flow through small apertures, experiments had been made with a very narrow glass beaker of 0·18 cm. internal diameter. The results which are given in Figure 1 show a normal transport rate which is practically independent of the film height. We are inclined to ascribe the small variation which was actually observed not so much to a real change in the flow rate but to a slight variation of the diameter of the beaker over its length. This is the more probable since in the following experiment the same variation was observed.

In order to repeat Atkins' observations, a glass bulb of 1·6 cm. diameter was blown on to the end of this beaker. The transfer was again examined, the results being included in Figure 1. A number of runs were made with the beaker filling while the mouth of the capillary was near the bath level. As can be seen, the transport rate is indeed higher in this region, reaching about twice the normal value when the film was 0·1 cm. high. However, at a height of only 0·8 cm. above the bath the rate had become normal. Emptying rates were taken between 2 and 3 cm. height, and these too are normal, being practically coincident with the measurements on the plain beaker.

Thus our results completely fail to confirm those of Atkins, and show no difference from the great number of our former observations on various types of beaker. The slight increase in the flow rate near the mouth of the beaker had already been noted by Daunt and Mendelssohn (1939 a) in their first experiment, and had been made the subject of close investigation. It was then suspected, and subsequently proved (Daunt and Mendelssohn 1939 b), that the entropy of the helium flowing through the film might be smaller than that of the bulk liquid. Thermal effects are then to be expected to occur at the ends of the film, and these might influence the flow rate. Accordingly a number of experiments with Dewar beakers had been carried out which proved conclusively that these thermal effects do *not* influence the film flow in this type of experiment. Atkins' suggestion that the large and variable flow rates found by him should be caused by thermal effects would therefore, in view of these earlier experiments, not appear convincing.

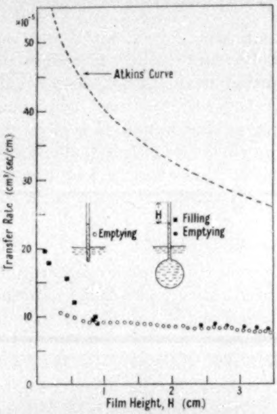
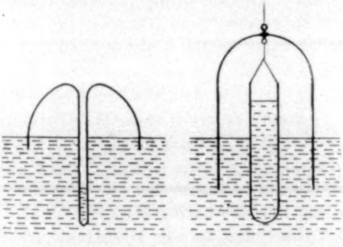


Figure 1. Effect of bulb on transfer rate (1·37° K.).



a *b*

Figure 2. Transfer vessels.

It was subsequently learnt that our arrangement differed in one respect from that used by Atkins.* The neck of our vessel was made up from a thin-walled glass tube, whereas Atkins had used the conventional type of capillary with a stout wall. The possibility could not be excluded that for some unknown reason the large glass surface which in this case was in contact with the inner wall of the tube might affect the transport rate. In order to produce similar geometrical conditions a thick-walled glass sleeve whose inside just fitted over the neck of our vessel was cemented on to it. An experiment in which the film flow into and out of this modified vessel was measured yielded, however, the same result as before.

Further experiments designed to investigate the possible influence of a large surface in contact with the mouth of the vessel were made with the small umbrella-like beaker shown in Figure 2(*a*). Here a thin-walled capillary of 0·074 cm. inside diameter had sealed around its lip a glass skirt of 1 cm. maximum width. With this beaker, too, only normal flow rates were recorded. In another experiment the outer and inner surfaces of an ordinary beaker had been ground to a matt finish with carborundum powder for a distance of approximately 1 cm. from the rim. Here again normal transport rates were recorded.

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* We are indebted to Dr. Atkins for communicating to us the contents of his paper before publication and for informing us of unpublished details of his work.

Since it was thought that possibly the pumping off of the helium bath might influence the rate of film transfer an arrangement was tried in which the helium vapour in contact with the film was not removed. It consisted of an ordinary beaker which was suspended under a glass hood dipping into the helium bath (Figure 2 (*b*)). Thus, any vapour evaporating from the surface of the beaker or the bath in the immediate vicinity was forced to condense in the same neighbourhood, instead of being pumped away. While here, too, only normal transfer took place, an interesting phenomenon was observed.

Above the lambda-point it was easy to establish a difference in level height between the liquid helium under the hood and the outer bath. When, now, the hood was pulled partly out of the bath or pushed further into it, it was found that while this level difference always re-established itself, it could be seen to lag by about one second behind this movement. At any sudden change in the position of the hood the level underneath it at first tended to follow this shift. Below the lambda-point, on the other hand, it was quite impossible to produce any level difference at all. Even when the hood was raised as quickly as possible (at several centimetres per second) clear of the bath, or pushed down, equally quickly, completely under the surface, no difference between the two levels could be observed, even momentarily. The fact that a measurable time was needed for the levels to attain equilibrium when the hood was moved in helium I, whereas it was reached so rapidly as to be undetectable in helium II, is direct evidence of the great thermal conductivity of the latter as compared with the former. In helium II the heat conduction is clearly so great that, when the vapour is subjected to a slight under-pressure or over-pressure, condensation or evaporation can take place instantaneously. The significant feature of the present experiment is that in this case the thermal contact concerned is directly between the free liquid and the vapour, and no question arises as to the heat contact between the liquid and a solid surface. This is worthy of note since it has sometimes been suggested that the heat conduction of the liquid itself, when no solid surface is involved, may be small.

§ 3. EFFECTS OF TEMPERATURE DIFFERENCE

Atkins' second set of experiments was based on his hypothesis that the high flow rates should be due to a temperature difference at the ends of the film. It has been pointed out above that our earlier experiments obviate the possibility of a change in the transport rate caused by thermal effects in experiments where no heat is supplied from outside. Moreover, Atkins' explanation of increased film flow in a temperature gradient would appear to be in contradiction to our earlier observations. In one of these experiments (Daunt and Mendelssohn 1939 a) the transfer rate has been found quite unchanged when one end of the film had been evaporated with an eddy current heater. Another example is provided by the observations on the thermo-mechanical effect in films (Daunt and Mendelssohn 1939 b, 1950), where one of the most salient features was the occurrence of the *same* transfer rate in thermal as in gravitational flow. Furthermore, the evaporation rates originally observed by Rollin and Simon (1939), which are of the same order as the normal transfer rate, also refer to film flow in a temperature gradient.

Nevertheless the issue seemed sufficiently important, and the arrangement used by Atkins sufficiently different, to warrant a repetition of his experiment. As in our experiments on the thermo-mechanical effect, Atkins used a small Dewar vessel to the inside of which heat could be supplied electrically. However, in his case communication through the gas phase was practically inhibited by a glass lid which formed a ground joint with the mouth of the vessel. Flow rates of about four times the normal into this vessel were observed when the temperature inside exceeded that of the helium bath by about 2×10^{-3} deg. K.

Besides any possible falsification of his results by impurities (to be discussed in the next paper, Bowers and Mendelssohn 1950), there was one particular objection to Atkins' arrangement in that it introduced doubt as to which circumference should be taken as the limiting perimeter of the film. Geometrically, the narrowest perimeter between the bulk liquid in the vessel and in the bath is provided by the inside circumference of the former, and this was the length used by Atkins in his computation. However, it has to be remembered that the inside of the beaker is warmer and that the height at which free bulk liquid can be formed with respect to the bath is not given by the inside meniscus but by the thermo-mechanical pressure difference. In the experiment described by Atkins this pressure corresponded to a level difference of 3 cm. while the height of the film amounted to only 0·9 cm. It was therefore quite possible for bulk liquid to form in the ground joint and to run down over the inside wall into the beaker. This would make, of course, the *outer* circumference, which was several times larger than the inner one, the limiting perimeter for the film flow.

Our arrangement was almost identical with that used by Atkins, except that in order to avoid the ambiguous geometry of his vessel we made the inner perimeter larger than the outer. This made it certain that the latter had to be used in the evaluation of the transfer rate. The apparatus is shown in Figure 3. D is a small unsilvered Dewar vessel of 1·5 cm. outer and 0·85 cm. inner diameter and 12 cm. long. It is closed by the glass plug P which forms with the vessel the ground joint J. The narrow end of the plug is continued as a cylindrical glass tube G of 0·75 cm. outer diameter to the bottom of the vessel. In this way the total internal perimeter of the beaker in direct contact with the joint ($\sim$5 cm.) exceeds the outer circumference ($\sim$4·7 cm.). The upper end of the plug is joined to the copper tube C, to which a copper radiation shield R is soldered. The vessel is held in position by two small springs Z. The tube G carries at its lower end the heating coil H and the thermometer T, the leads (not shown) of which leave the apparatus by the platinum–glass seals S. In order to minimize the heat influx a wick of cotton wool which dipped into the helium bath was wound round S. Readings of the helium level in the Dewar were taken through the observation window W. In the first experiments a phosphor-bronze thermometer was used which was later replaced by a wire of leaded brass of higher sensitivity. However, since the chief aim was to study the film flow under comparatively high temperature gradients no greater sensitivity than approximately $0{\cdot}5 \times 10^{-3}$ deg. was required.

A typical result is shown in Figure 4, which gives the observed transport rates into the beaker at 1·37° K. Different heater currents were used, which resulted in temperature differences varying between 0·9 and 35×10^{-3} deg. As can be seen, the flow rate was practically constant and in good agreement with the normal rate of transfer observed by Daunt and Mendelssohn. There is a slight apparent drop in the rate with the highest heat current, which is due to evaporation. At a still (approximately 10 times) higher heat current this evaporation became so large that the level actually fell, the vapour evidently escaping through the ground joint. There is always a small amount of stray heat entering arrangements of this kind, which in our case resulted in a temperature difference of rather less than 3×10^{-4} deg.* This was at the limit of sensitivity of our thermometer, but the temperature difference could be conveniently measured by the produced thermo-mechanical pressure. The rate at which helium entered under these conditions was measured and found to be slightly smaller (see Figure 4) than with the higher heat currents.

The absolute value of the flow rate depends on an accurate knowledge of the minimum film perimeter and of the free cross section inside the vessel D. While the latter can be determined with fair accuracy, the former, being the entrance to the ground joint, is less easy to measure. There is also the uncertainty as to whether the small perimeter of the glass tube below C should be added to the total transfer perimeter or not. In this way an error of up to 20% can be introduced. In order to obtain an independent check, the in-and-out flow under gravity was also determined. The result, which is given in Figure 4, agrees with the rates obtained under the various temperature differences to within 5%. Thus, using the same arrangement for the determination of flow rates under gravity and in a temperature gradient, we have obtained a direct proof of the identity of these rates. This result fully confirms the conclusions reached by Daunt and Mendelssohn (1950) but is in wide disagreement with Atkins' observations.

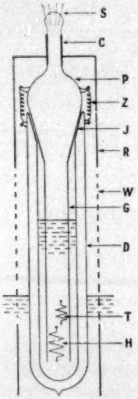

Figure 3. Apparatus for measuring transfer in a temperature gradient.

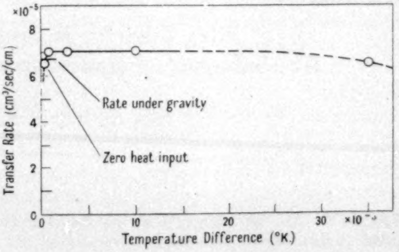

Figure 4. Transfer rate in a temperature gradient.

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* The graph given by Atkins suggests that the heat influx into his apparatus was slightly larger but of the same order of magnitude.

§4. CONCLUSIONS

Summarizing our results, we must conclude that, except for the spurious effects mentioned in the introduction, we have found no evidence whatever for high flow rates through the helium film as caused by the geometrical form of the experimental arrangement or by a temperature gradient. In particular, we have completely failed to reproduce the results obtained by Atkins, although we have used apparatus practically identical with that employed by him. It has to be emphasized that the disagreement is far too wide to be explained by any kind of observational error.

We regard as a valuable positive result the direct demonstration of the identity of the transfer rate under gravity and of that in a temperature gradient. This identity serves to indicate the existence of a *critical* rate in the flow phenomena of liquid helium II. It is hoped that further reduction of heat influx into an arrangement as described in this paper will make it possible to study the phenomena of sub-critical film flow.

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Film Transfer in Helium II: III—Influence of Radiation and Impurities

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ABSTRACT. In contradiction to the results of de Haas and van den Berg, the complete exclusion of thermal radiation has not been found to increase the transfer rate beyond the normal value. It was observed, however, that contamination of the transfer surface with condensed gases will cause a greatly increased film flow. The effect of impurities on the transfer has been studied in detail and the conclusion has been reached that the high and variable transfer values recently reported by some observers are to be ascribed to this cause. The bearing of the effect on cryogenic technique is discussed.

§1. INTRODUCTION

The results of the investigations described in the preceding paper (Brown and Mendelssohn 1950) led to the unsatisfactory position that two almost identical sets of experiments, those carried out by Atkins (1948) and our own, disagreed completely. The question as to whether the rate of film transport is a quantity which only depends on the absolute temperature and which is largely uninfluenced by the experimental arrangement, as postulated by us, or whether, as suggested by the Cambridge results, it may vary widely is of considerable importance. It has been pointed out (Mendelssohn 1947) that observations on films are of special interest because they permit the study of pure 'superfluidity' to the exclusion of viscous flow. An invariant transport rate in films would therefore indicate the existence of a limiting velocity in the flow phenomena in liquid helium II. It is worthy of note that the theories of liquid helium do not on the whole yield such a critical velocity, and recent interpretations have tended to ignore its existence. It had for these reasons to be considered significant when recently de Haas and van den Berg (1949) in Leiden also reported* the observation of very high and *variable* rates of film transport. Their experiments were carried out in the orthodox fashion by measuring the outflow from a beaker, but the whole arrangement was completely enclosed, the weight of the beaker being determined by means of a sensitive balance. With this apparatus transport rates very similar to those found by Atkins were recorded, with values of nearly twenty times the normal rate near the rim of the beaker and decreasing over its length. De Haas and van den Berg suggest that these high rates are caused by the complete absence of radiation, which would allow a much thicker film to be deposited. This thick film is supposed to show quite different transfer properties, acting very much like an ordinary siphon. Quite apart from the objections which might be raised against the validity of the argument used by these authors to account for the thick film,† their interpretation of the observed phenomena is not wholly convincing. In particular, it was surprising that thick films yielding high transfer rates should have been formed in the experiments at Cambridge, which were carried out in a cryostat with visual observation. On the other hand, special care had been taken in all our experiments (cf. Daunt and Mendelssohn 1939 a) to reduce heat influx to a minimum. In view of the wide discrepancy, and because the experiments could be carried out with comparative ease, the observations of the Leiden authors with completely shielded beakers were repeated.

§ 2. EFFECTS OF RADIATION

An obvious weakness of the Leiden work was the omission of a control experiment to demonstrate conclusively that, *ceteris paribus*, small amounts of radiation would inhibit the occurrence of high transport rates. We therefore used two arrangements which allowed us in each case to study the film transfer with *and* without radiation. In the first set of experiments a glass beaker was used, the top half of which was completely enclosed in a copper box while the lower part was visible. Figure 1 shows a typical result. The empty beaker was lowered into the helium bath and transfer into the beaker was observed with the outer level below the copper box. The ascending as well as the descending film were in this case exposed to radiation. After 18 minutes the beaker was further lowered so that the lower end of the box dipped into the bath. It was known from our earlier work that at any place below the highest liquid level helium can run down in the form of drops, so that now the whole length of the actual film path was shielded by the box. As can be seen, there is very little difference between the two rates of inflow. Actually, the rate under shielded conditions corresponds exactly to that determined by Daunt and Mendelssohn, while the 'unshielded rate' is about 12% lower. Further tests showed that it was not, in fact, illumination of the exposed film which caused this small decrease in transfer, but the radiation impinging on the copper box.

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* Through the kindness of Professor F. E. Simon the results of these authors were made available to us before publication.

† De Haas and van den Berg postulate a curious process of re-condensation of helium from the bulk liquid on to the emerging film. They say : " As is well known, the temperature of the film creeping out of the liquid is lower than the mean value of the temperature, while at the same time at the point of the liquid where the film leaves, the temperature is higher than the mean value." No evidence is quoted in support of this statement except that reference is made to the mechano-caloric effect. When we reported on the discovery of this effect (Daunt and Mendelssohn 1939 b) we were careful to state that *the heat content of the helium transported by surface flow must be lower than average.* This does not, of course, permit any conclusion as to either the entropy of the film as a whole or to its temperature. In fact our experiments on the isolation of the film (Brown and Mendelssohn 1947) have shown that it has the same vapour pressure as the bulk liquid. Furthermore, in view of the experiments with the hooded beaker mentioned by Brown and Mendelssohn (1950), it must appear very doubtful whether temperature gradients such as visualized by de Haas and van den Berg can exist in bulk liquid helium II.

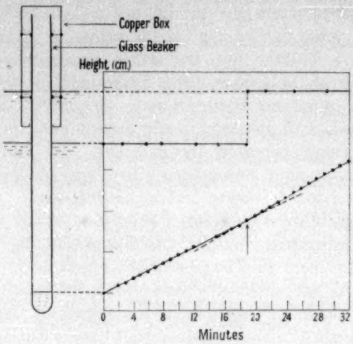

Figure 1. First experiment on the influence of radiation.

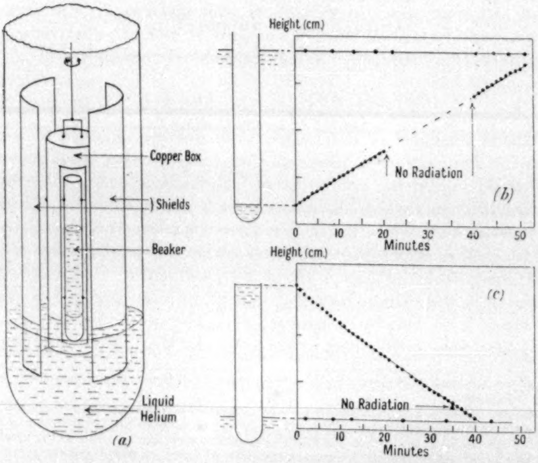

Figure 2. Second experiment on the influence of radiation.

In the first part of the experiment this box was suspended above the bath level without touching the liquid and was possibly slightly warmer, causing some evaporation of the film. Subsequent experiments with radiation shields in the surrounding bath of liquid air removed this cause of error.

The arrangement used for the second set of experiments is shown in Figure 2 (*a*). A glass beaker is suspended in a cylindrical copper box which has observation slits on opposite sides. This box can be raised or lowered with respect to the helium bath, and it can also be turned around a vertical axis. In this manner the observation slits can either be turned into the direction of the light or they can be opposed to a pair of radiation shields. In the latter case the beaker will only receive radiation of the same temperature as that of the film. Two types of experiment were carried out with this arrangement. In the first kind, an example of which is illustrated in Figure 2 (*b*), the transfer was observed alternately with and without radiation in the course of the same run. With helium flowing into the beaker, the transfer was observed for the first 20 minutes. Then the copper box was turned and radiation excluded for the next 20 minutes. At minute 40 the box was turned back again and observations were made for another 11 minutes. As can be seen from the diagram all the points lie on a straight line, showing that no change occurred in the transfer rate while radiation was excluded. The absolute value of the rate, moreover, is in good agreement with that determined in our previous work. The second type of experiment was performed because it was thought that in order to get high transfer rates it may be necessary to exclude radiation right from the start of the transfer. In the example shown in Figure 2 (*c*) the beaker was first completely submerged and then pulled out into the position in which visual observation could be made. The record shows that, as usual after a very slightly raised transfer rate, within 1 cm. from the rim, the rate had settled down to its normal value by the tenth minute and remained steady for the rest of the observation. After the beaker had been emptied again, the experiment was repeated but without radiation. At minute 35 the box was turned and the height of the level noted. This height (marked by the triangle in the diagrams) agrees very well with that obtained under radiation in the preceding experiment.

§ 3. EFFECT OF IMPURITIES

After the above experiments had demonstrated our complete inability to reproduce not only the results of Atkins but also those of de Haas and van den Berg, the conclusion was inescapable that neither the geometrical shape nor the temperature gradient nor the absence of radiation could be held responsible for the appearance of high transfer rates. On the other hand it seemed significant that these high rates had been found in Cambridge and Leiden with a wide variety of experimental arrangements but were completely missing in our observations. We therefore began to suspect that the real cause for the high transfer rates might have to be sought in some subtle difference in experimental technique rather than in the physical conditions postulated by Atkins and de Haas.

A careful analysis of such earlier data as are available showed that high transfer rates must in fact have occurred in the attempts of Kamerlingh Onnes (1922) and of Keesom (1932) to reach very low temperatures by pumping off liquid helium. The former remarks on the rapidity with which the helium levels reached equal height, and the figures given by the latter for the loss of liquid from his Dewar vessel are much higher than can be accounted for by ordinary transfer. Equally suspicious is the large scatter of evaporation rates in similar experiments carried out more recently by Blaisse, Cooke and Hull (1939). A common feature of all these experiments, as well as of the transfer observations of de Haas and van den Berg, is that helium gas was *condensed* into the experimental space in a cold cryostat. It occurred to us that, should this helium gas have contained some impurity, the latter would probably condense in the gas stream and finally settle on the solid surfaces carrying the transfer. We had also reason to believe that the state of the surface might be significant since it had been found to influence the desorption of thick layers of helium (Mendelssohn and Closs 1932) which were probably akin to the film later discovered by Rollin and Simon (1939). In the work of Atkins condensation was usually not employed and the cryostat was filled directly with liquid helium. However, it seemed significant that in these experiments high transfer rates were definitely associated with transfer vessels having a narrow neck in which any impurity in the helium was more likely to settle than in an open beaker. This possible explanation also fitted in with the occasional observations of high rates in the case of closed vessels with a small aperture mentioned by Brown and Mendelssohn (1950).

It was therefore of interest to investigate the influence of the transfer of such impurity as might accidentally enter a helium cryostat. The tests were made with an ordinary straight glass beaker of about 0·3 cm. internal diameter without the use of any radiation shield. After filling our cryostat in the usual manner with liquid helium and decreasing its vapour pressure to that corresponding to a temperature below the lambda-point (1·33° K.), the transfer from this beaker was measured and found to be in agreement with our previous value. Then the helium pump was shut off and a small amount of helium gas admitted into the cryostat from the low pressure pipe line. This line connects the exhaust of the helium pump with a storage gas-holder and contains helium gas at atmospheric pressure. Owing to very slight leakage into the pump (probably through the oil) the gas in this line usually contains also a small amount of air. After allowing this gas to enter, the helium pump was again connected and the liquid was cooled below the lambda-point for another transfer observation.

Even before readings were taken it became clear that conditions in the cryostat had changed. A gas thermometer is attached to the tube through which the helium vapour is pumped off at a place somewhat below the point where this tube enters the surrounding bath of liquid hydrogen. Usually this thermometer registers a temperature of 12°–15° K. when the helium bath is being pumped off. In the present case it indicated a much lower temperature ($\sim 5°$ K.), thereby showing that a much larger amount of cold helium gas was passing through the tube than normally. This anomalously high evaporation of liquid helium was verified by the reading of a flowmeter in the pump line. The walls of the cryostat and the glass beaker now appeared to be covered with a translucent deposit of solid air. This deposit was white in reflected light but showed a definitely brownish colour when light was passing through it. It somewhat resembled fog in its optical properties, and we therefore conclude that the deposit was granular in character with a particle size of the same order of magnitude as the wavelengths of visible light. It was evidently the existence of a similar deposit of solid air on the inner wall of the pumping tube which was responsible for the increased evaporation from the helium bath.

The subsequent transfer experiment did indeed give results completely at variance with the preceding one. As the beaker was lifted out of the bath the helium level in the former dropped so rapidly that the change in height was immediately apparent. Measurement showed that the transfer rate near the rim was more than ten times higher than the normal rate. The rate, however, decreased gradually as the level in the beaker fell until it attained the normal value, which was then maintained. In fact the transfer phenomenon now exhibited exactly the features observed in Cambridge and Leiden.

It is interesting to note that in depositing the contamination we had followed a procedure which simulated closely the conditions under which helium gas would be admitted into a cryostat for condensation. The tube through which the gas was allowed to enter first passed through a container with liquid air and then through the bath of liquid hydrogen before leading into the helium vessel. These precautions clearly do *not* prevent solid air from being deposited on the transfer surfaces in the experimental space. This fact would seem to support the view that the impurity may condense in the stream of helium gas as it is cooled on entering the apparatus and that the crystallites formed in this way can be carried into the cryostat itself.

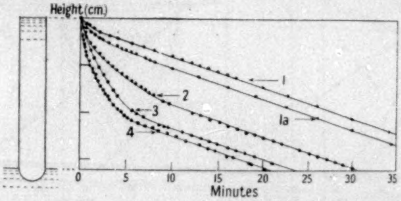

Figure 3. 1, clean beaker; 1a, adsorbed air; 2, 3 and 4, successive deposits of solid air.

Following the first successful experiment a considerable number of observations was made on the effect of varying degrees of contamination with air, hydrogen and neon. For this purpose gas mixtures were prepared containing helium and about 1·5 volume per cent of the impurity. Small amounts of these mixtures were admitted in successive steps into the cryostat and a transfer experiment was made after each additional contamination. All experiments were preceded by a transfer observation with pure helium which in each case yielded the normal rate.

The results obtained with deposits of solid air are shown in Figure 3. Curve 1 gives the normal transfer with pure helium. The first batch of impure helium did not produce a visible layer of contamination on either the beaker or the walls of the cryostat. The only indication of a precipitate was provided by a few completely transparent flakes which had evidently formed on the liquid surface and slowly fell to the bottom of the helium container. Nevertheless, as is shown by curve 2, the character of the transfer had changed very much. This change was further emphasized by the second (curve 3) and third (curve 4) batch of impurity. No further change in the transfer curve was effected by a fourth batch of impurity which as yet had not resulted in any visible deposit on the beaker. Only after two rather larger amounts of impure helium had been admitted was a visible layer of solid air formed on the glass surface which was similar to the deposit observed in the first test experiment. The rate of transfer in these two cases was exactly identical with that of curve 4. The fact that the last four deposits yielded observations all falling on the same curve shows that there exists a saturation of the glass surface with impurity and that additional contamination will not produce a further increase in the transfer rate. With regard to Atkins' observations it seems significant that a layer of solid air which is sufficient to give this saturation rate is still too thin to be seen.

The curve 1a which is included in this diagram is taken from a separate experiment carried out with the same arrangement. In this case the glass beaker was left in contact with dry air at slightly less than atmospheric pressure at a temperature of 90° K. before the cryostat was filled with liquid helium. Although the air was pumped out at this temperature, an adsorbed layer of air was almost certainly left on the beaker. As can be seen, the transfer rate under these conditions is somewhat higher than the normal rate near the rim of the beaker, but the effect is comparatively slight.

Similar series of experiments with hydrogen and neon (Figures 4 (*a*) and (*b*) respectively) gave essentially the same results as contamination with solid air. The initial experiment with neon did not yield a high transfer rate and it was first thought that deposits of this substance behaved differently from air and hydrogen. Subsequent attempts at producing high rates with neon were, however, successful, and we are inclined to ascribe this erratic behaviour to the fact that it seems difficult to produce adherent layers of solid neon on glass.

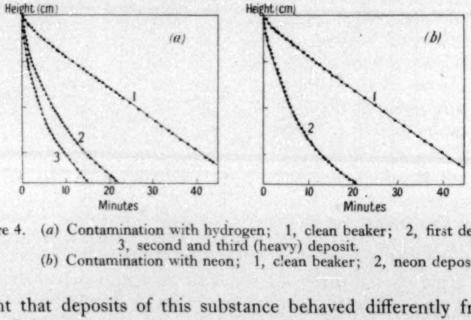

Figure 4. (*a*) Contamination with hydrogen; 1, clean beaker; 2, first deposit; 3, second and third (heavy) deposit.
(*b*) Contamination with neon; 1, clean beaker; 2, neon deposit.

The next problem to be solved was to account for the curious shape of the transfer curve. De Haas and van den Berg suggest that the high transfer shows 'the character of siphoning', and Atkins too mentions the possibility that it may follow the laws of viscous flow. On the other hand, our curves can certainly not be considered exponential functions. A possible explanation for the shape of these curves, however, comes immediately to mind on considering the cause for the anomalously high transfer. All our experiments show that the rate changes with the degree of contamination. Thus along a glass surface covered with a solid air deposit of varying thickness* the total transfer will be limited by the thinnest part of the layer. In view of the manner in which the contamination is deposited, one has reason to believe that, particularly along the inner wall of the beaker, the layer of solid air varies in thickness, being heaviest at the rim and then decreasing gradually towards the lower end. The thickness of the deposit would thus play the same part as the width of the connecting surface in normal transfer, where it has been found (Daunt and Mendelssohn 1939 a) that the narrowest perimeter above the upper liquid level imposes a limit on the film flow. Therefore, as the liquid level in the contaminated beaker drops, it will expose an air deposit of gradually decreasing strength which in turn progressively restricts the transfer. This interpretation would also agree well with Atkins' suggestion that the transfer seemed to depend rather on the distance of the level from the top of his vessel than on the level difference.

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* In this context the term 'thickness' of the layer is merely meant to indicate the amount of impurity deposited per unit glass surface. The deposit being evidently granular, it is quite possible that variations in 'thickness' actually are variations in grain density on the glass surface.

In order to test our hypothesis we measured the transfer *into* a beaker with contaminated surface. These experiments were carried out after the observations shown in Figure 3, i.e. on a beaker with a heavy deposit of solid air. Three fillings in all were observed with the outer level at constant heights of 0·6, 1·1 and 1·8 cm. respectively below the rim of the beaker. As the results in Figure 5 (*a*) show, the transfer curves are now perfectly straight lines, demonstrating that the flow rate, as in all normal transfer experiments, is independent of the level difference. The siphon explanation proposed by de Haas and van den Berg therefore appears to be incorrect. If, on the other hand, our hypothesis is right, we should expect the transfer rate to be sensibly the same for the same height of the *upper* level irrespective of whether this happens to be the inner or the outer level. We have therefore plotted in Figure 5 (*b*) three straight lines of the same steepness as the transfer curves of Figure 5 (*a*) together with the saturation transfer curve of Figure 3. With good approximation these lines form indeed the tangents to the outflow curve at heights of 0·6, 1·1 and 1·8 cm. from the rim, thus demonstrating directly that at a given height the transfer rate is the same from the inner *or* the outer level.*

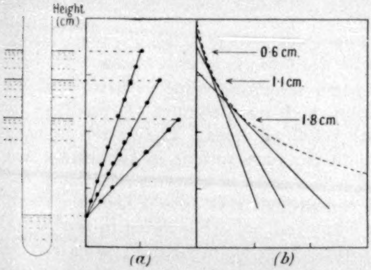

Figure 5. Transfer into contaminated beaker.

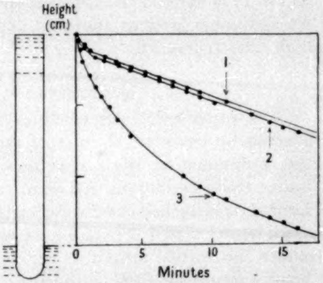

Figure 6. 1, clean beaker; 2, contamination on outer wall only; 3, contamination on inside and outside.

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* This explanation would also account for the curious fact that all our transfer curves ultimately end in straight lines which are parallel to that for uncontaminated flow. Below a certain distance from the rim, the wall of the beaker (probably on the inside) will not be covered any more with solid air, and the transfer then must be limited to its normal value.

As a final check on our findings that the high transfer rates are caused by contamination and on our hypothesis concerning the shape of the transfer curve, it was decided to examine a beaker of which the outside wall only was contaminated. We expected to achieve this condition by simply filling the beaker with liquid helium, lifting it out of the bath completely and quickly admitting impure helium into the cryostat. However, the results of the subsequent observations were disappointing, always yielding curves of the type 2, 3 or 4 of Figure 3. It was then found that a layer of contamination would be deposited even below the liquid surface. In fact, when a clean beaker was kept completely submerged in the helium bath while the impure gas was admitted, it nevertheless showed high flow rates in a subsequent transfer observation. The difficulty of depositing a layer on the outside only was finally overcome by keeping the temperature of the cryostat above the lambda-point and rapidly admitting a fairly large amount of impure gas as soon as the beaker had been lifted out of the bath. It was observed that owing to the large heat influx the liquid in the beaker boiled violently while at the same time a clearly visible layer of impurity settled on the beaker. The strong ebullition of vapour evidently succeeded in preventing the contaminated gas from entering the beaker. Figure 6 shows that the transfer rate after this procedure (curve 2) was practically identical with the rate for the clean beaker (curve 1) in spite of the fact that the outside was thickly covered with a deposit. An additional layer of impurity, deposited in the usual manner, then gave again high rates (curve 3).

§4. CONCLUSIONS

The experiments described in this paper show that while the transfer is not affected by complete absence of radiation, high transfer rates are produced by the contamination of glass surfaces with solidified gases. The results obtained under these conditions are identical with the observations in Cambridge and Leiden, which, however, were ascribed to a variety of other causes. Since our work shows that it is possible for such contamination to enter a helium cryostat under the normal procedure generally employed, we are inclined to ascribe the results found by these authors also to the action of impurities. This view is strengthened by the fact that our repetition of their work carried out under clean conditions never yielded high transfer rates. Our results have in the meantime * been confirmed by Atkins (1949), who has in fact stated that the high transfer rates observed by him earlier were due to contamination. Further confirmation has been provided by Burge and Jackson (1950), who repeated our comparison of clean and contaminated surfaces and obtained results similar to ours.

While our results show unambiguously that a layer of solidified gas deposited on a glass surface will increase the transfer rate very appreciably, the actual reason for this increase is by no means clear. Two possible explanations appear obvious. Either the geometrical transfer perimeter may simply be increased by the deposit, or the molecular forces exerted by the different substrates on the helium film may influence the transfer in some unknown manner. A definite decision between these alternatives is at present not possible although, as will be further discussed in the fourth paper in this series (Mendelssohn and White 1950), the first explanation seems rather more likely.

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* A short note on our experiments was published more than a year ago (Bowers and Mendelssohn 1949).

There is, however, a purely practical aspect of the problem on which our results can be turned to immediate use. One of the chief difficulties in cryogenic technique at temperatures below 2·19° K. is to reduce the heat influx due to film transfer and re-condensation of helium gas. There is little doubt that many of the erratic results and high evaporation rates mentioned earlier were caused by contamination in the connecting tubes of the helium cryostats. Our experiments show that even small amounts of condensed gases will cause a much increased transfer and that this contamination can pass into the cryostat although the temperature of the latter may be well below the melting point of the impurity. This means that care must be taken in experiments of this kind to use only helium of very high purity and to pump out the apparatus thoroughly at ordinary temperatures. It is clearly not sufficient for purification merely to pass the condensing gas through a tube immersed in liquid hydrogen, and even small air leaks into the cryostat or pumping line must be scrupulously avoided.

ACKNOWLEDGMENT

One of us (R. B.) is indebted to the Department of Scientific and Industrial Research for a research grant.

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Film Transfer in Helium II: IV—The Transfer Rate on Glass and Metals

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MS. received 24th July 1950

ABSTRACT. The rate of transfer R has been measured as a function of temperature along surfaces of glass, platinum and nickel. While the (R, T) curves have all approximately the same shape, the absolute values of R on metals were found to be much higher than on glass. The effects of polishing and degassing of the transfer surfaces have been studied. Possible explanations for the observed effects are discussed.

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§ 1. INTRODUCTION

THE dependence of the rate of transfer on temperature had been measured in the early experiments of Daunt and Mendelssohn (1939 a, b), but it appeared desirable for a number of reasons to repeat and supplement these data. Various aspects of the work on liquid helium II carried out since have indicated that all the transport phenomena seem to be distinguished by a critical velocity or flow rate which in turn appears to be directly linked with the concentration of the 'superfluid component'. Since the film exhibits the purest, and evidently also the simplest, example of frictionless flow, an accurate determination of its transfer rate as a function of temperature is of particular interest. The early experiments showed that as the temperature is lowered the curve of transfer rate rises with a finite slope from the value zero at the lambda-point, eventually becoming almost independent of temperature at approximately 1·5° K. This general behaviour was confirmed in the numerous incidental observations on clean glass surfaces carried out in this laboratory in the intervening years. However, none of these experiments was designed with the purpose of determining the temperature dependence of the transfer rate, and it was therefore desirable to make this quantity the subject of a separate investigation.

Another aspect to be considered is the nature and the physical state of the solid surface over which the film flow takes place. Practically all experiments providing quantitative data have been carried out on glass surfaces, and it is probable that in most, if not in all, cases the glass was covered by an adsorbed layer of water. In view of the strong influence of contamination by solidified gases on the transfer described by Bowers and Mendelssohn (1949, 1950), it appeared imperative to examine carefully dried and degassed surfaces. A re-examination of the influence of materials other than glass on the transfer also seemed to be indicated. Daunt and Mendelssohn (1939 a, b) had found that a polished copper beaker yielded the same rates as glass, but some experiments with copper wires had provided considerably higher values of flow. Further data on these phenomena would not only be valuable for a better understanding of the physical nature of film flow, but they would also be helpful for the design of such cryogenic equipment in which small film transfer is essential. Experiments on the influence of temperature and substrate were therefore undertaken. A short preliminary note on some of the results has been published elsewhere (Mendelssohn and White 1950).

§2. TRANSFER ON GLASS

The experiments were carried out in the hooded glass beaker shown in Figure 1 (*a*), the hood being designed to give better thermal protection and to prevent direct evaporation from the beaker. The beaker was made of a Pyrex glass tube with an inner radius of 0·1126 ± 0·0006 cm., with its upper end ground flat and rigidly attached at the sealed lower end inside a glass hood of about 1 cm. diameter. The hood was surrounded by a cylindrical radiation shield of copper which had on opposite sides two vertical observation slits 3·5 mm. wide. For the first experiment the beaker was cleaned in carbon tetrachloride, chromic acid, and distilled water before being fixed inside the glass hood and then the assembly was placed in the cryostat. After a brief pumping out of the experimental space at room temperature, helium was liquefied and the transfer rate was determined at seven different temperatures below the lambda-point.

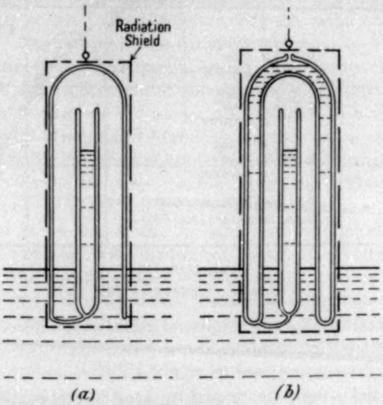

Figure 1.

The transfer rates obtained from emptying the beaker showed a dependence of flow on the height of the liquid level over about 2 cm. from the rim of the beaker. Furthermore, when filling the beaker, the transfer rate within two or three millimetres of the rim was found to be 50% higher. These observations indicated a similar behaviour to that observed on layers of adsorbed air and showed that the glass surface should be degassed more thoroughly.

For the next experiments the glass parts of the cryostat with the beaker inside were surrounded by warm water at about 50° C. and pumped out for an hour with a rotary oil pump before each experiment. The results of this series of observations (G_1A) are shown in Figure 2. Above 1·7° K. they are somewhat higher and below this temperature slightly lower than the original values of Daunt and Mendelssohn (1939 a, b), reaching sensibly the same value at 1·2° K. In the individual determinations the transfer rate R was found to be independent of the height of the level at any part of the beaker except within about 5 mm. of the rim and when the levels approach to within about 3 mm. In the former case R is about 40% higher than over the length of the beaker and in the latter about 8 to 12% lower. A slight increase near the edge seems to be common to all transfer observations, but is evidently not due to thermal effects (Daunt and Mendelssohn 1939 a, b). Over the length of the beaker, R was generally found to be constant to within 2% of its absolute value. There appears to be, however, a significant difference between the emptying and the filling rates, the latter being consistently higher by $5 \pm 2\%$. These figures refer to the temperature-independent part of R, while near the lambda-point in some cases larger discrepancies between filling and emptying rates were observed. It has to be remembered of course that in this region the absolute value of R becomes very small. The most obvious explanation that the difference between the two rates may be apparent and simply be caused by greater evaporation from one level would suggest an effect in the opposite direction. One might think of heat absorbed by the glass beaker causing its contents to evaporate, but this would naturally simulate a higher emptying rate.

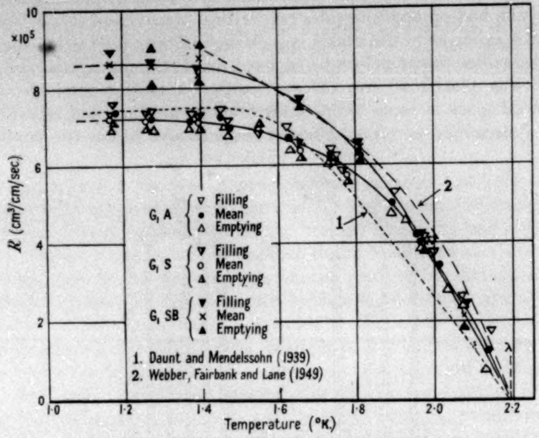

Figure 2. Transfer on glass.

However, in order to see whether further exclusion of heat influx would produce a change, the experimental arrangement was modified as shown in Figure 1 (*b*). The plain glass hood was replaced by a double-walled glass cover which could be kept filled with liquid helium. The whole arrangement was again surrounded by a radiation shield. In this way radiation had to pass through a 3-mm. wall of liquid helium and two glass walls having certainly the same temperature as the helium bath. The same inner beaker was used as in the previous experiments and again pumped at a temperature of 50° c. before the liquefaction. The results obtained in this series (G_1S) are also shown in Figure 2, and it can be seen that within the experimental error R is of the same magnitude as in G_1A. However, there is again a difference of the same order between the filling and the emptying rates, the former being again higher.

For the next series of experiments, the beaker with its double-walled glass hood and radiation shield was left in the cryostat but immediately before the next liquefaction the whole arrangement was baked out at about 130° c. This was done in an electric oven surrounding the cryostat which during this time (1½ to 2 hours) was pumped to a vacuum of about 10^{-3} mm. Hg. The results for this third series (G_1SB), shown in Figure 2, exhibit the same general shape of the (R, T) curve, but the absolute values at least below 1·9° K. are approximately 20% higher than in G_1S and G_1A. Although in two cases (1·28° and 1·4° K.) high emptying rates were observed, there is in general the same discrepancy between emptying and filling rates as in the previous determination. The higher transfer within a few millimetres of the rim was also found in these experiments as well as a lower transfer when the difference between the levels was less than 3 mm. We have also given in Figure 2 the curve recently obtained by Webber, Fairbank and Lane (1949), which shows on the whole somewhat higher values than ours, but of the same order of magnitude.

No adequate explanation can be offered for the difference in R between inflow and outflow. The effect is small and is likely to be swamped as soon as the scatter of values is greater, as was indeed the case with the metal surfaces described in the next section. Nevertheless, the observations seem to be too consistent to dismiss the difference as an experimental error. The fact that the same behaviour was found in G_1A and G_1S seems to rule out the possibility of the effect being caused by external radiation. It seems also difficult to account for it by the mechano-caloric effect (Daunt and Mendelssohn 1939 b), since this is a reversible phenomenon. Possibly the effect of higher transfer near the rim may be extended in a much smaller degree for some distance along the beaker. Since on filling the average height of the outer level is nearer to the rim than the average height of the inner level is on emptying, an apparent difference between the two processes would be caused. As mentioned above, R is constant to within 2% along the beaker, but it appears that such curvature as does exist is more pronounced on emptying. The increased transfer near the rim still persisted after baking out and can therefore hardly be ascribed to adsorbed water or air. This, as well as the increased total value of R over the length of the beaker in comparison with the unbaked beaker, may be due to surface roughness as will be discussed later. Thus while it is tempting to see in the observed variation of R a true, if slight, dependence on the *height* of the film above the liquid level, the effect is so small that we hesitate to regard it at present as being of fundamental significance.

§3. TRANSFER ON METAL

Having obtained somewhat increased transfer rates over the glass surface after baking, and thereby presumably removing part of the adsorbed water layer, experiments were carried out on metal beakers which could be baked to much higher temperatures than was possible with glass. The construction of the cryostat makes it difficult to raise the temperature of the glass beakers inside it to more than about 150° c. without endangering the copper–glass seals and the soldered metal joints of the liquefier unit. Metal beakers, on the other hand, can be subjected to some form of localized radiation heating which will raise their temperature considerably without affecting the remainder of the cryostat.

The arrangement used for the transfer observations is shown in Figure 3. The beaker was suspended so that it could slide up and down freely in a glass tube which was closed at the bottom and had a small hole at the top through which the suspension wire passed. The beaker was centred in the glass tube by three points at each end and this tube was supported and centred in the cryostat by a radiation shield of copper. To determine R, visual observations were made on the level of helium in the annular space between beaker and glass tube. In the typical graph shown in Figure 3, the change of this level is represented by $x-y$. The change of the inner level $x'-y$ is, of course, unobservable in the case of a metal beaker. When the two levels inside and outside the beaker coincided at y, observations were continued so as to determine the zero drift due to evaporation and film transfer through the small hole in the top of the glass tube. Thus by subtracting the zero drift $y-z$ from the slope of $x-y$, a true value of the transfer from the beaker could be obtained. If dH/dt is the corrected rate of change of the level outside, and dh/dt that of the level inside the metal beaker, the transfer rate R is related to the observable quantity,

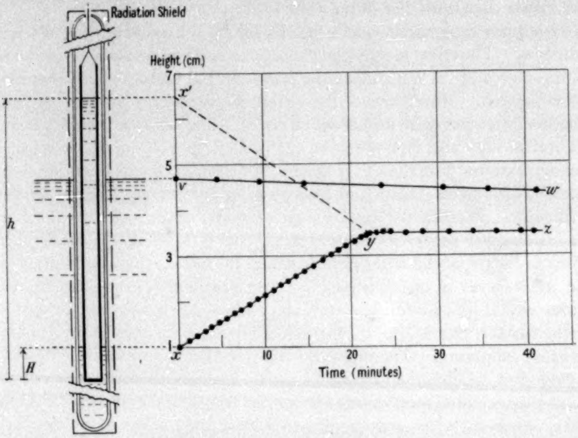

Figure 3. Arrangement with metal beaker.

$$\frac{dH}{dt} = \frac{2a_1R}{(b-a_0)(b+a_0)} \text{ cm}^3/\text{sec/cm.},$$

and to the unobservable quantity

$$\frac{dh}{dt} = \frac{2R}{a_1} \text{ cm/sec.},$$

where a_1 and a_0 are the inner and outer radii of the beaker and b the inner radius of the glass tube.

In a case where the level H crosses the bath level $v-w$, the slope $x-y$ changes abruptly owing to a reversal of the direction of film transfer through the small hole. In most cases therefore, emptying and filling rates at any given temperature were taken with the bath level not crossing so that the drift conditions remained unchanged.

Observations were made with a platinum beaker cut from a length of drawn tube of inner and outer diameters 0·365 cm. and $0{\cdot}400_5$ cm. respectively. For the first experiments the beaker was cleaned in carbon tetrachloride, hot concentrated hydrochloric acid and distilled water. It was then degassed inside the cryostat at 50° c. for more than an hour before liquefaction. The character of the transfer was similar to that found on glass, but it was slightly less regular along the length of the beaker. Although *R* was found to be quite constant over a distance of a centimetre or more, sudden decreases in its value of up to 5% occurred at irregular intervals. Since the value of *R* always decreased with falling level difference, the changes may possibly be due to purely geometrical conditions of the surface restricting the transfer.

The absolute value of *R* in dependence on temperature is shown in Figure 4 (Pt A). The points indicate means between inflow and outflow observations, and they are about twice as high as those on clean glass. There is a peculiar fall of the rate with lower temperatures which was also observed on glass beakers by Daunt and Mendelssohn. No explanation can be offered for this drop except that it suggests that, in certain cases at least, the transfer is governed by two processes having different temperature dependences.

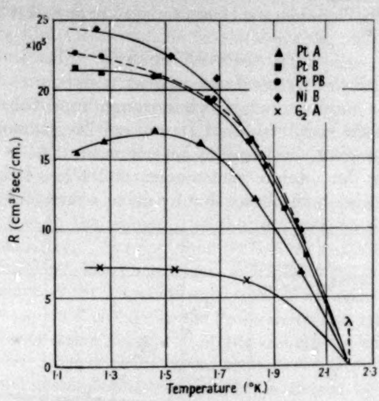

Figure 4. Transfer on metal.

Before the next experiments the beaker was heated to about 600° c. and degassed at a pressure of approximately 10^{-3} mm. Hg for an hour. The baking was achieved by means of a 750-watt projector lamp with a hemispherical reflector behind it, focusing on to the centre of the beaker. The transfer values found now (Pt B) are about 25% higher than before and do not drop at the lowest temperatures.

Finally, the outer surface of the beaker was polished on a lathe, using fine emery powder and jeweller's rouge. It was then baked again at 600° as previously. The results obtained (Pt PB) are very similar to those for the unpolished beaker, except that they yield still higher values of *R* below 1·3° K.

Since the possibility could not be excluded that the high flow rates on the platinum beaker might be simulated by a porosity of the platinum tube, measurements on another metal surface seemed desirable. A beaker of similar dimensions to the platinum one was turned from a solid nickel rod, polished and cleaned with carbon tetrachloride, then dipped into warm hydrochloric acid and washed in distilled water. After being placed in the cryostat, the nickel beaker was baked at 600° c. prior to liquefaction. Apart from a slightly increased value near the edge and a slightly decreased transfer on approach of the inner and outer level, R was found to be completely constant over the length of this beaker. The absolute values given in Figure 4 (Ni B) are again very high, almost $3\frac{1}{2}$ times those on glass, and are very close to those of Pt PB.

As a final check on the experimental arrangement used, the metal beakers were replaced by a glass beaker of similar dimensions. When transfer values were obtained on this beaker after degassing, they were found to be of the normal magnitude (Figure 4, G_2A). The conclusion therefore seems inescapable that the transfer is actually higher on a surface of platinum or nickel than on glass.

§ 4. CONCLUSIONS

All the curves of the transfer rate against temperature obtained in this investigation show a similar trend, which in rough approximation, though not in detail, resembles the early results of Daunt and Mendelssohn. In order to compare the different (R, T) curves, they have been brought to the same scale in Figure 5 by making the absolute values agree at 1·4° K. It can be seen that, in spite of the variation in absolute value by up to a factor of approximately 3, the shape of the transfer curves is almost identical. The two dotted lines represent the mathematical functions :

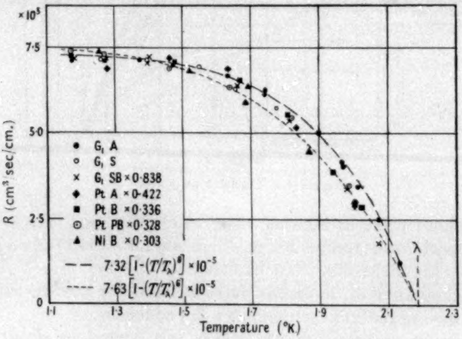

Figure 5. Comparison of transfer rates.

$$R = 7{\cdot}32\left[1 - \left(\frac{T}{T_\lambda}\right)^8\right] \times 10^{-5}; \qquad R = 7{\cdot}63\left[1 - \left(\frac{T}{T_\lambda}\right)^6\right] \times 10^{-5}.$$

Except for the results on the unbaked glass beaker, the values are fairly well represented by the sixth power function.

This result is of interest in connection with the two-fluid concept (Tisza 1947) in which the concentration of the superfluid component ρ_s is represented by a function $\rho_s = \rho[1 - (T/T_\lambda)^\sigma]$, where ρ is the total density of the liquid. Experiments on second sound and on the inertia of the fluid (Peshkov 1946, Andronikashvilli 1946) suggest a value of the order of six for the exponent σ.

It has been suggested by Daunt and Mendelssohn (1942) that the change of the transfer rate with temperature may indicate the change of the superfluid concentration, and this idea has been followed up by theoretical considerations of F. London (1945). The hypothesis implies that the average particle velocity would be independent of temperature and this led to the assumption (Mendelssohn 1945) that the momentum of the superflow is provided by the zero-point energy. Taken in conjunction with the results from second sound and inertia observation, the (R, T) curve determined in the present work thus supports the existence of a temperature-independent velocity.

The hypothetical relation between the rate of frictionless mass flow and indeterminacy (Daunt and Mendelssohn 1946) immediately leads to an independence of the transfer of the height of the film. If, as can be expected, the thickness of the film varies with its height above the bulk liquid, one has to postulate a proportionality between the flow velocity and the inverse film thickness in order to maintain a constant transfer rate. Such a mechanism seems indeed to be provided by the uncertainty relation $v \sim h/md$, where d is a linear dimension of the order of the film thickness. These considerations are of importance when we now consider the difference in the absolute values of the transfer rates on glass and metal surfaces.

Since we do not yet have a satisfactory theory for the formation of the transfer film, considerations as to the influence of the substrate on the rate of transfer have to remain speculative. As mentioned by Bowers and Mendelssohn (1950), two obvious alternatives offer themselves as explanation. We must assume either that the difference in intermolecular forces between the film and the different substrates causes a change in the flow rate or that simply, owing to its micro-structure, the effective perimeter of the underlying surface varies from case to case. Taking the first case, it is unfortunately not sufficient to postulate merely different thicknesses of the transfer film as caused by the different type of force exerted from the material of the substrate on the helium atoms. Even if one could argue that metal atoms would hold a thicker helium film than glass or water molecules, this would not result automatically in a higher transfer rate. The experiments show that over metal surfaces, too, the transfer is independent of the difference in level height, and to explain this, one still has to admit the existence of a mechanism which makes the velocity vary inversely with the film thickness. Consequently a thicker film would have a proportionately smaller velocity and the transfer rate would again be the same on glass and metal.* It is therefore clear that, in order to attribute the variation of transfer rate to the inter-atomic forces, one must postulate a mechanism in which the particle velocity in helium is directly influenced by the forces exerted from the atoms of the substrate. While such a mechanism can of course not be ruled out, it is at present not easy to see how it could operate.

For these reasons the second explanation, that of a purely geometrical increase in the solid surface carrying the transfer would appear somewhat more probable. It has to be remembered that on the polished copper beaker investigated by Daunt and Mendelssohn the same transfer rate was observed as on glass, although the possibility cannot be excluded that this was simulated by an additional layer of water on the copper. On the other hand, if the high transfer rates are simply caused by surface roughness, it is necessary for this roughness to extend over the whole length of the beaker. A region of smooth surface on the wall of the beaker would clearly limit the transfer anywhere along the beaker wall below this level. The present experiments give indeed some indication that in some cases there are discontinuities in the rate which produce a progressively smaller flow as a greater length of the beaker is exposed. These indications are, however, too slight to allow a definite decision. The experiments on contamination of the transfer surface with condensed gases have shown that the variation of the transfer rate with height is, in fact, due to a variation of the nature of the substrate over the length of the beaker, and that in all cases the character of the flow remains pressure independent. The required increase in perimeter to account for the higher transfer on metal would have to be about threefold. But it should be kept in mind that this figure is only valid when one considers surface irregularities much larger than the film thickness (of the order of 10^{-6} cm.). Once one admitted the existence of surface cracks allowing some kind of capillary flow, which would still be pressure independent, the required increase in effective perimeter would be much smaller. There is some indication in our experiments that heat treatment of glass as well as of metals increases the transfer rate, and one has some reason to believe that heating may either produce cracks in a smooth surface or expose cracks which were formerly filled with adsorbed water molecules. However, clearly a good deal more detailed investigation on the micro-structure of the solid surfaces employed in the transfer is required before this tentative explanation can be substantiated.

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* This argument must become invalid if the dependence of film thickness on height is very weak. However, changes in R corresponding to the directly observed thickness variation (Burge and Jackson 1949) would have easily been noticed in our experiments.

For the present one can conclude that for the purely practical purposes of limiting the film flow in cryostats, it appears preferable to use glass rather than metal surfaces. It also seems desirable to extend the restricting perimeter over a centimetre or more so as to make sure that any accidentally occurring regions of high transfer are excluded from the tube leading into the cryostat.

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The Disintegration of the Deuteron by Neutron Impact

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Communicated by H. S. W. Massey; *MS. received* 23*rd March* 1950

ABSTRACT. The method of distorted waves is applied consistently to the calculation of the cross section for disintegration of deuterons by neutrons. At an incident neutron energy of 11·5 MEV. the cross section calculated for the process ($6{\cdot}4\times10^{-25}$ cm²) is about one-third that obtained in previous calculations but is nevertheless an order of magnitude greater than that indicated by the rather meagre experimental data. The calculated cross section is also larger than the maximum permitted by considerations of the conservation laws. This indicates that the n–d interaction is so strong that the requirements for the validity of the distorted wave method are not satisfied.

At an incident neutron energy of 5·1 MEV. where it is considerably less than the permitted maximum, the calculated cross section is of the same order of magnitude as that deduced indirectly from measurements of the p–d disintegration cross section, allowing for the effects of the electrostatic repulsion between the proton and the deuteron.

Although the most direct evidence about the nature of the interaction between nucleons is likely to be obtained from a study of the scattering of protons and neutrons by protons, important information can also be expected from a detailed study of the three-body scattering problem.

Calculations were made by Buckingham and Massey (1941, 1947) of n–d and p–d scattering using the resonating group structure method. In these calculations the nucleonic interaction was assumed to be purely central, to have the exchange properties of the symmetrical meson theory, and to be represented in shape by an exponential well. Such an interaction gives good agreement with the measured total cross section for n–d scattering and the differential cross section for p–d scattering. The agreement also seems to be fair for the angular distribution of neutrons of energy about 2·5 MEV. scattered by deuterons, but the result in this case is not so conclusive because of discrepancies between the results of different experimenters. Calculations carried out (Burhop and Massey 1948) of the radiative capture cross section of neutrons by deuterons using the same assumed interaction show a cross section consistent with the meagre published experimental data.

It seemed of interest therefore to calculate the cross section for the disintegration of the deuteron by neutrons using the same interaction constants, particularly as the availability of intense sources of homogeneous neutrons of energy 14 MEV. from the d–t reaction is likely to make possible a more accurate experimental determination of the cross section.

§ 1. GENERAL THEORY

In the ^3S state the neutron–proton interaction was taken as

$$V(r) = -A\exp(-2r/a)$$

with $A=242\ mc^2$, $a=1{\cdot}73\times10^{-13}$ cm². These are the constants calculated by Present and Rarita (1937) to give the best binding energy of the light nuclei.

The interaction in the other states was assumed to be connected with that in the ^{3}S state by the following relations:

$$\left.\begin{aligned} {}^1V_{\text{even}} &= 0{\cdot}6\,{}^3V_{\text{even}}, \\ {}^3V_{\text{odd}} &= -\tfrac{1}{3}\,{}^3V_{\text{even}}, \\ {}^1V_{\text{odd}} &= -3\,{}^1V_{\text{even}}. \end{aligned}\right\} \qquad \ldots\ldots(1)$$

Following the procedure of papers I and II the group structure method of Wheeler (1937) has been used to represent the three-body wave functions. The three-particle states may be either doublets or quartets. If α, β are the spin wave functions corresponding to the two possible spin orientations for each nucleon, the three-particle wave functions take the following forms:

$$\begin{aligned} {}^2\psi_{1/2}:\ & (12)^{-1/2}[\{\alpha(1)\alpha(2)\beta(3)+\alpha(1)\beta(2)\alpha(3)-2\beta(1)\alpha(2)\alpha(3)\}\phi_{\text{d}}(23,1) \\ & -\{\alpha(2)\alpha(1)\beta(3)+\alpha(2)\beta(1)\alpha(3)-2\beta(2)\alpha(1)\alpha(3)\}\phi_{\text{d}}(13,2)], \qquad \ldots\ldots(2\,a) \end{aligned}$$

${}^2\psi_{-1/2}$: As for ${}^2\psi_{1/2}$ but with α and β interchanged, ...(2 *b*)

$${}^4\psi_{3/2}:\ (2)^{-1/2}\alpha(1)\alpha(2)\alpha(3)[\phi_{\text{q}}(23,1)-\phi_{\text{q}}(13,2)], \qquad \ldots\ldots(2\,c)$$

$${}^4\psi_{1/2}:\ (6)^{-1/2}\{\alpha(1)\alpha(2)\beta(3)+\beta(1)\alpha(2)\alpha(3)+\alpha(1)\beta(2)\alpha(3)\}\{\phi_{\text{q}}(23,1)-\phi_{\text{q}}(13,2)\}, \qquad \ldots\ldots(2\,d)$$

${}^4\psi_{-1/2}$: As for ${}^4\psi_{1/2}$ but with α and β interchanged, ...(2 *e*)

${}^4\psi_{-3/2}$: As for ${}^4\psi_{3/2}$ but with α and β interchanged. ......(2 *f*)

In these expressions (1) and (2) refer to the coordinates of the two neutrons and (3) to those of the proton. $\phi(23,1)$ is the spatial wave function in which the neutron 2 may be regarded as grouped with the proton to form a deuteron.

$\phi(23,1)$ is expanded in the form

$$\phi(23,1)=F_{k_0}(\mathbf{r})\chi_0(\mathbf{u})+\int F_{k'}(\mathbf{r})\chi_\kappa(\mathbf{u})\,d\kappa, \qquad \ldots\ldots(3)$$

where, if $\mathbf{r}_1$, $\mathbf{r}_2$, $\mathbf{r}_3$ are the position vectors of particles 1, 2, and 3,

$$\mathbf{u}=\mathbf{r}_3-\mathbf{r}_2, \qquad \mathbf{r}=\tfrac{1}{2}(\mathbf{r}_2+\mathbf{r}_3)-\mathbf{r}_1.$$

$\chi_0(\mathbf{u})$ is here the wave function of the deuteron in its ground state and $\chi_\kappa(\mathbf{u})$ its wave function in the state of positive energy $\kappa^2\hbar^2/M$ of the system. $F_{k_0}(\mathbf{r})$ may be regarded as a wave function representing the motion of the incident neutron relative to the centre of mass of particles 2 and 3 in the initial state. $F_{k'}(\mathbf{r})$ is the corresponding wave function when the deuteron has been excited to the state of ionization represented by $\chi_\kappa(\mathbf{u})$. In (3) the only term in the summation corresponding to bound states is $F_{k_0}(\mathbf{r})\chi_0(\mathbf{u})$ since only one bound state of the deuteron exists. The function $\chi_\kappa(\mathbf{u})$ is normalized per unit κ in the usual way (Sommerfeld 1930) by the relation

$$\int_{\kappa-\frac{1}{2}d\kappa}^{\kappa+\frac{1}{2}d\kappa} d\kappa' \int \chi_{\kappa'}(\mathbf{u})\chi_\kappa^*(\mathbf{u})\,d\mathbf{u}=1. \qquad \ldots\ldots(4)$$

The asymptotic forms of $F_{k_0}(\mathbf{r})$, $F_{k'}(\mathbf{r})$ are

$$F_{k_0}(\mathbf{r})\sim\exp(ik_0z)+r^{-1}\exp(ik_0r)f_0(\theta,\phi). \qquad \ldots\ldots(5)$$

$$F_{k'}(\mathbf{r})\sim r^{-1}\exp(ik'r)f_{k'}(\theta,\phi). \qquad \ldots\ldots(6)$$

Introducing the vectors $\mathbf{v}=\mathbf{r}_3-\mathbf{r}_1$ $\mathbf{t}=\mathbf{r}_2-\mathbf{r}_1$, $\mathbf{r}'=\frac{1}{2}(\mathbf{r}_1+\mathbf{r}_3)-\mathbf{r}_2$ and writing $V(u)$ for the interaction (including exchange operators) between the nucleons 2 and 3, the functions ψ of equation (2) have to satisfy the wave equation

$$\{T+V(u)+V(v)+V(t)\}\psi=E\psi \qquad \ldots\ldots(7)$$

with

$$T=-(\hbar^2/M)(\nabla_u{}^2+\tfrac{3}{4}\nabla_r{}^2)=-(\hbar^2/M)(\nabla_v{}^2+\tfrac{3}{4}\nabla_{r'}{}^2),$$

$$E=E_0+E_{k_0}=E_\kappa+E_{k'},$$

where E_{k_0}, $E_{k'}$ are the energies of motion relative to the centre of mass of the system in the initial and final states, E_0, E_κ respectively the (negative) energy of the ground state of the deuteron and the (positive) energy of the final state of the deuteron represented by the wave function $\chi_\kappa(u)$, and M is the mass of a nucleon.

The following relations hold between the E's and the k's:

$$E_{k_0}=\tfrac{3}{4}k_0{}^2\hbar^2/M;\ \ E_{k'}=\tfrac{3}{4}k'^2\hbar^2/M;\ \ E_{\kappa_1}=\kappa_1{}^2\hbar/M.$$

Equations for $F_{k'}(\mathbf{r})$, $F_{k_0}(\mathbf{r})$ now have to be obtained. The method of distorted waves is used (Mott and Massey 1949, p. 144). The expansion (3) for $\phi(23,1)$ is replaced by

$$\phi(23,1)=F_{k_0}(\mathbf{r})\chi_0(\mathbf{u})+F_{k'}(\mathbf{r})\int_{\kappa-\frac{1}{2}d\kappa}^{\kappa+\frac{1}{2}d\kappa}\chi_{\kappa'}(\mathbf{u})\,d\kappa', \qquad \ldots\ldots(8)$$

where κ' lies in the interval $\kappa-\frac{1}{2}d\kappa$, $\kappa+\frac{1}{2}d\kappa$ thus ignoring, in the expansion for $\phi(23,1)$, all terms except those involving the initial and final states of the deuteron.

Consider a ${}^4\psi_{3/2}$ initial state. Substitute from equations (2 *c*) and (8) in (7), multiply throughout by $\alpha(1)\alpha(2)\alpha(3)$ and sum over the spin coordinates. The terms in $\nabla_u{}^2\chi_\kappa(\mathbf{u})$, $\nabla_u{}^2\chi_0(\mathbf{u})$ can be eliminated by using the relations

$$\left.\begin{aligned}\{-(\hbar^2/M)\nabla_u{}^2+V(u)\}\chi_\kappa(\mathbf{u})&=E_\kappa\chi_\kappa(\mathbf{u}),\\ \{-(\hbar^2/M)\nabla_u{}^2+V(u)\}\chi_0(\mathbf{u})&=E_0\chi_0(\mathbf{u}).\end{aligned}\right\}$$

Multiplying throughout by $\chi_\kappa^*(\mathbf{u})$ and integrating over u space, the resulting equation contains terms of the form

$$\int\chi_0(\mathbf{v})\chi_\kappa^*(\mathbf{u})\nabla_{r'}{}^2F_{k_0}(\mathbf{r}')\,d\mathbf{u}$$

which can be transformed by means of Green's theorem to the form

$$(4/3)^3\Big[(4M/9\hbar^2)\int\chi_\kappa^*(\mathbf{u})\chi_0(\mathbf{v})F_0(\mathbf{r}')\{-4E_\kappa-E_0+V(v)+4V(u)\}\,d\mathbf{r}'\Big]$$
$$+(16/9)\int\nabla_u\chi_\kappa(\mathbf{u})\,.\,\nabla_v\chi_0(\mathbf{v})F_0(\mathbf{r}')\,d\mathbf{r}'. \qquad \ldots\ldots(9)$$

Finally the integro-differential equations for $F_{k'}(\mathbf{r})$, $F_{k_0}(\mathbf{r})$ are obtained in the form

$$(\nabla^2+k'^2)F_{k'}(\mathbf{r})+G_{\kappa\kappa}(\mathbf{r})=G_{0\kappa}(\mathbf{r}), \qquad \ldots\ldots(10\,a)$$

$$(\nabla^2+k_0{}^2)Fk_0(\mathbf{r})+G_{00}(\mathbf{r})=G_{\kappa0}(\mathbf{r}), \qquad \ldots\ldots(10\,b)$$

where

$$G_{0\kappa}(\mathbf{r})=\alpha U_{0\kappa}F_0(\mathbf{r})+\int\{\beta Q_{0\kappa}(\mathbf{r},\mathbf{r}')+\gamma P_{0\kappa}{}^{(1)}(\mathbf{r},\mathbf{r}')+\delta P_{0\kappa}{}^{(2)}(\mathbf{r},\mathbf{r}')$$
$$+\epsilon(E_\kappa/E_0-4E_{k'}/3E_0-1/3)N_{0\kappa}(\mathbf{r},\mathbf{r}')\}F_0(\mathbf{r}')\,d\mathbf{r}' \qquad \ldots\ldots(10\,c)$$

in which

$$\left.\begin{aligned} U_{0\kappa} &= (4M/3\hbar^2)\int \chi_0(\mathbf{u})\chi_\kappa^*(\mathbf{u})V(t)\,d\mathbf{u},\\ Q_{0\kappa}(\mathbf{r},\mathbf{r}') &= (4M/3\hbar^2)(4/3)^3\chi_0(\mathbf{v})V(t)\chi_\kappa^*(\mathbf{u}),\\ P_{0\kappa}^{(1)}(\mathbf{r},\mathbf{r}') &= (4M/9\hbar^2)(4/3)^3\chi_0(\mathbf{v})\{V(u)+V(v)\}\chi_\kappa^*(\mathbf{u}),\\ P_{0\kappa}^{(2)}(\mathbf{r},\mathbf{r}') &= (4/3)^5\nabla_u\chi_\kappa^*(\mathbf{u})\,.\,\nabla_v\chi_0(\mathbf{v}),\\ N_{0\kappa}(\mathbf{r},\mathbf{r}') &= (M/\hbar^2)(4/3)^4E_0\chi_0(\mathbf{v})\chi_\kappa^*(\mathbf{u}), \end{aligned}\right\} \quad \ldots\ldots(11)$$

and α, β, γ, δ, ϵ are constants which depend on the parity of $\chi_\kappa(\mathbf{u})$ and are given in Table 1.

Table 1

	α	β	γ	δ	ϵ
Quartet (χ_κ even)	0	1	1	1	1
Quartet (χ_κ odd)	$-\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	1	1
Doublet (χ_κ even)	0	1·6	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$
Doublet (χ_κ odd)	0·567	−0·533	$-\frac{1}{6}$	$-\frac{1}{2}$	$-\frac{1}{2}$

Very similar expressions can be written down for G_{00}, $G_{\kappa\kappa}$. In the method of distorted waves the term $G_{\kappa 0}(\mathbf{r})$ on the right-hand side of (10*b*) is neglected since products of the type $U_{\kappa 0}F_\kappa$ are much less important than those of the type $U_{0\kappa}F_0$.

The same equations are obtained if the initial quartet state is given by (2*d*). For doublet states the analysis is very similar and an expression similar to (10*c*) is obtained but with different constants, as is seen from Table 1.

The solution of (10*a*) with asymptotic form (6) gives

$$\begin{aligned} f_{k'}(\theta,\phi) = -(4\pi)^{-1}\Big[\alpha\int &\mathscr{F}_\kappa(r,\pi-\Theta)U_{0\kappa}F_{k0}(\mathbf{r})\,d\mathbf{r}\\ &+\iint\{\beta Q_{0\kappa}(\mathbf{r},\mathbf{r}')+\gamma P_{0\kappa}^{(1)}(\mathbf{r},\mathbf{r}')+\delta P_{0\kappa}^{(2)}(\mathbf{r},\mathbf{r}')\\ &+\epsilon(E_\kappa/E_0-4E_{k'}/3E_0-1/3)N_{0\kappa}(\mathbf{r},\mathbf{r}')\}F_{k_0}(\mathbf{r}')\mathscr{F}_\kappa^*(r,\pi-\Theta)\,d\mathbf{r}\,d\mathbf{r}'\Big] \end{aligned} \quad \ldots\ldots(12)$$

in which $\mathscr{F}_\kappa(r,\theta)$ is the solution of

$$\begin{aligned} (\nabla^2+k'^2)\mathscr{F}_\kappa(\mathbf{r}) = \alpha' U_{\kappa\kappa}(\mathbf{r})&\mathscr{F}_\kappa(\mathbf{r})\\ &+\int\{\beta' Q_{\kappa\kappa}(\mathbf{r},\mathbf{r}')+\gamma' P_{\kappa\kappa}^{(1)}(\mathbf{r},\mathbf{r}')+\delta' P_{\kappa\kappa}^{(2)}(\mathbf{r},\mathbf{r}')\\ &+\epsilon'(E_\kappa/E_0-8E_{k'}/3E_0+1)N_{\kappa\kappa}(\mathbf{r},\mathbf{r}')\}\mathscr{F}_\kappa(\mathbf{r}')\,d\mathbf{r}' \end{aligned} \quad \ldots\ldots(13)$$

with the asymptotic form

$$\mathscr{F}_\kappa(r,\theta)\sim\exp(ik'z)+r^{-1}\exp(ik'r)f_{k'}(\theta,\phi)$$

and

$$\begin{aligned} U_{\kappa\kappa}(\mathbf{r}) &= (4M/3\hbar^2)\int d\kappa'\int\chi_{\kappa'}(\mathbf{u})\chi_\kappa^*(\mathbf{u})V(t)\,d\mathbf{u},\\ Q_{\kappa\kappa}(\mathbf{r},\mathbf{r}') &= (4M/3\hbar^2)(4/3)^3\int\chi_{\kappa'}(\mathbf{v})\chi_\kappa^*(\mathbf{u})V(t)\,d\kappa',\\ P_{\kappa\kappa}^{(1)}(\mathbf{r},\mathbf{r}') &= (4M/9\hbar^2)(4/3)^3\int\chi_{\kappa'}(\mathbf{v})\{V(v)+V(u)\}\chi_\kappa^*(\mathbf{u})\,d\kappa',\\ P_{\kappa\kappa}^{(2)}(\mathbf{r},\mathbf{r}') &= (4/3)^5\int\nabla_u\chi_{\kappa'}^*(\mathbf{u})\,.\,\nabla_v\chi_\kappa(\mathbf{v})\,d\kappa',\\ N_{\kappa\kappa}(\mathbf{r},\mathbf{r}') &= (M/\hbar^2)(4/3)^4E_0\int\chi_{\kappa'}(\mathbf{v})\chi_\kappa^*(\mathbf{u})\,d\kappa' \end{aligned}$$

and α', β', γ', δ', ϵ' are constants. In each case the limits of the integration over κ' are $\kappa-\frac{1}{2}d\kappa$ to $\kappa+\frac{1}{2}d\kappa$.

With the method of normalization of χ_κ used, all the terms on the right-hand side clearly vanish when $d\kappa \to 0$ with the exception of terms arising from modes of disintegration in which two particles remain close together even after disintegration. Since the probability of this mode is infinitesimal, it is justifiable to take for $\mathscr{F}_\kappa^*(r, \pi - \Theta)$ in (12) the form $\exp(-ik'\mathbf{n}.\mathbf{r})$ where $\mathbf{n}$ is a unit vector in the direction of scattering.

$F_{k_0}(r)$ is the solution of (10 *b*) $[G_{\kappa 0}(r) = 0]$ with asymptotic form

$$F_{k_0}(r) \sim \exp(ik_0 z) + r^{-1} \exp(ik_0 r) f_{k_0}(\theta, \phi).$$

Putting in appropriate weighting factors for the quartet and doublet states, the differential cross section for scattering of neutrons of momentum $k_0\hbar\mathbf{n}$ into the direction $\mathbf{n}(\theta, \phi)$ while the wave number of the ejected electron lies between κ_1 and $\kappa + d\kappa$, is obtained finally in the form

$$I(\theta, \phi, k')\, d\Omega\, d\kappa = (k'/k_0)\{\tfrac{1}{3}|f_{k'}{}^{\mathrm{D}}(\theta, \phi)|^2 + \tfrac{2}{3}|f_{k'}{}^{\mathrm{Q}}(\theta, \phi)|^2\}\, d\Omega\, d\kappa, \qquad \ldots\ldots(14)$$

where $f_{k'}{}^{\mathrm{D}}$, $f_{k'}{}^{\mathrm{Q}}$ refer to the doublet and quartet states respectively and the amplitudes are obtained by substituting in (12) the appropriate constants from Table 1.

The total cross section $Q(k_0)$ for the disintegration process is then given by

$$Q(k_0) = \iiint I(\theta, \phi, k') \sin\theta\, d\theta\, d\phi\, d\kappa, \qquad \ldots\ldots(15)$$

where the integration over θ, ϕ is carried out over a complete sphere and that over κ for all values from 0 to $\kappa_{\max}$ where $\kappa^2_{\max} = \frac{3}{4}k_0{}^2 - \kappa_0{}^2$, $\kappa_0{}^2\hbar^2/M$ being the binding energy of the ground state of the deuteron.

In calculating (15), the momentum κh of the ejected neutron (or proton) relative to the centre of mass of the deuteron is given by

$$\kappa^2 = \tfrac{3}{4}(k_0{}^2 - k'^2) - \kappa_0{}^2. \qquad \ldots\ldots(16)$$

§ 2. CALCULATION OF $f_\kappa{}^{\mathrm{D}}$, $f_\kappa{}^{\mathrm{Q}}$

The main difficulty in the calculation of these amplitudes consists in the evaluation of the terms $Q_{0\kappa}$, $P_{0\kappa}{}^{(1)}$, $P_{0\kappa}{}^{(2)}$, $N_{0\kappa}$ depending on the deuteron wave function in its initial bound state and in its final state of positive energy.

For the initial state the wave function appropriate for the exponential interaction (first given by Massey and Mohr 1934, 1935) was used, viz. :

$$\chi_0 = (0{\cdot}7084/r),\ J_{0\cdot 4}\{(MA)^{1/2}\, a \exp(-r/a)/\hbar\}. \qquad \ldots\ldots(17)$$

For the positive energy state

$$\left.\begin{aligned} \chi_\kappa{}^{\mathrm{s}} &= (2^{1/2}\pi r)^{-1} f_0(\kappa r), \\ \chi_\kappa{}^{\mathrm{p}} &= 3^{1/2}(2^{1/2}\pi r)^{-1} f_1(\kappa r) \cos\vartheta, \end{aligned}\right\} \qquad \ldots\ldots(18)$$

where $\chi_\kappa{}^{\mathrm{s}}$, $\chi_\kappa{}^{\mathrm{p}}$ are wave functions for neutrons ejected into s and p states respectively. These functions are normalized per unit wave number κ. The radial functions $f_0(\kappa r)$, $f_1(\kappa r)$ were calculated numerically for the motion of the ejected neutron in the field of the proton for a state of relative motion of energy $\kappa^2\hbar^2/M$. They were normalized to the asymptotic forms

$$f_0(\kappa r) \sim \sin(\kappa r + \eta_0);\quad f_1(\kappa r) \sim \sin(\kappa r - \pi/2 + \eta_1).$$

Let $Q_{0\kappa}$, $P_{0\kappa}{}^{(1)}$, $P_{0\kappa}{}^{(2)}$, $N_{0\kappa}$ refer now to the functions as defined above except that the angular quantity, $\cos\vartheta$ of equation (18), is omitted from χ_κ. Thus for the s state ejected neutron, $Q_{0\kappa}$, etc. have the same meaning as before but for the other states their meaning is slightly modified in this way.

These quantities can then be expanded as a series of harmonic functions of $\mathbf{r}\,.\,\mathbf{r}'$, viz.

$$\left.\begin{matrix} Q_{0\kappa}(\mathbf{r},\mathbf{r}') \\ P_{0\kappa}{}^{(1)}(\mathbf{r},\mathbf{r}') \\ P_{0\kappa}{}^{(2)}(\mathbf{r},\mathbf{r}') \\ N_{0\kappa}(\mathbf{r},\mathbf{r}') \end{matrix}\right\} = \sum_s P_s\left(\frac{\mathbf{r}\,.\,\mathbf{r}'}{rr'}\right)\left\{\begin{matrix} q_s{}^{\kappa}(r,r') \\ p_s{}^{\kappa(1)}(r,r') \\ p_s{}^{\kappa(2)}(r,r') \\ n_s{}^{\kappa}(r,r') \end{matrix}\right\} \qquad \ldots\ldots(19)$$

where

$$\left.\begin{matrix} q_s{}^{\kappa}(r,r') \\ p_s{}^{\kappa(1)}(r,r') \\ p_s{}^{\kappa(2)}(r,r') \\ n_s{}^{\kappa}(r,r') \end{matrix}\right\} = \frac{2s+1}{2}\int_{-1}^{1}\left\{\begin{matrix} Q_{0\kappa}(\mathbf{r},\mathbf{r}') \\ P_{0\kappa}{}^{(1)}(\mathbf{r},\mathbf{r}') \\ P_{0\kappa}{}^{(2)}(\mathbf{r},\mathbf{r}') \\ N_{0\kappa}(\mathbf{r},\mathbf{r}') \end{matrix}\right\} P_s\left(\frac{\mathbf{r}\,.\,\mathbf{r}'}{rr'}\right) d\left(\frac{\mathbf{r}\,.\,\mathbf{r}'}{rr'}\right). \qquad \ldots\ldots(20)$$

The function $F_0(\mathbf{r}')$ can be written

$$F_0(\mathbf{r}') = \sum_m (k_0 r')^{-1}(2m+1)i^m \exp(i\eta_m) g_m{}^i(k_0 r') P_m(\mathbf{n}_0\,.\,\mathbf{r}'/r'). \qquad \ldots\ldots(21)$$

The functions $g_m{}^i$ were calculated numerically for the motion of the incident neutron in the field of the deuteron and have the asymptotic form

$$g_m{}^i(k_0 r') \sim \sin(k_0 r' - m\pi/2 + \eta_m). \qquad \ldots\ldots(22)$$

For the function $\mathscr{F}_\kappa(r, \pi - \Theta)$, we write

$$\exp(-ik'\mathbf{n}\,.\,\mathbf{r}) = \sum_l (2l+1)(-i)^l f_l(r) P_l(\mathbf{n}\,.\,\mathbf{r}/r), \qquad \ldots\ldots(23)$$

where

$$f_l(r) = (\pi/2k'r)^{1/2} J_{l+1/2}(k'r). \qquad \ldots\ldots(24)$$

By carrying out the angular integrations in (12) and using the relation

$$\begin{aligned} P_s(\mathbf{r}\,.\,\mathbf{r}'/rr') = {} & P_s(\mathbf{n}_0\,.\,\mathbf{r}/r)P_s(\mathbf{n}_0\,.\,\mathbf{r}'/r') \\ & + 2\Sigma\{(s-p)!/(s+p)!\}P_s{}^p(\mathbf{n}_0\,.\,\mathbf{r}/r)P_s{}^p(\mathbf{n}_0\,.\,\mathbf{r}'/r')\cos p\,(\phi_1 - \phi_2) \end{aligned} \qquad \ldots\ldots(25)$$

and the similar one for $P_l(\mathbf{n}\,.\,\mathbf{r}/r)$ it is seen that if the ejected neutron is in an s state, $l = s = m$, while if it is in a p state, either $s = m$, $l = s \pm 1$ or $s = l$, $m = s \pm 1$.

The most important case is that for which the ejected neutron is in an s state and $l = m = s = 0$ so that

$$\begin{aligned} & \int\left\{\begin{matrix} Q_{0\kappa(s)} \\ P_{0\kappa(s)}{}^{(1)} \\ P_{0\kappa(s)}{}^{(2)} \\ N_{0\kappa(s)} \end{matrix}\right\} \mathscr{F}_\kappa(r, \pi - \Theta) F_0(\mathbf{r}')\, d\mathbf{r}\, d\mathbf{r}' \\ & \qquad = (16\pi^2 e^{i\eta_0}/k'k_0)\int\!\!\int\left\{\begin{matrix} q_{0(s)}{}^{\kappa} \\ p_{0(s)}{}^{\kappa(1)} \\ p_{0(s)}{}^{\kappa(2)} \\ n_{0(s)}{}^{\kappa} \end{matrix}\right\} g_0{}^i(k_0 r') \sin k'r\, rr'\, dr\, dr', \end{aligned} \qquad \ldots\ldots(26)$$

where the suffix s denotes that the kernels $q_{0(s)}^{\kappa}$ etc. refer to an s state ejected neutron.

When the ejected neutron is in a p state

$$\chi_{\kappa}{}^{\mathrm{p}}(u) = 3^{1/2}(2^{1/2}\pi u)^{-1} f_1(\kappa u)[4\mathbf{n}_0 . \mathbf{r}'/3 + 2\mathbf{n}_0 . \mathbf{r}/3]$$

and the integrations can be carried out in much the same way although the term $\nabla_u \chi_0 . \nabla_v \chi_\kappa$ leads to some complication in the calculation of $p_{0(\mathrm{p})}{}^{\kappa}$.

From Table 1 it is seen that for even states of χ_κ the coefficient α of the term $\int \mathscr{F}_\kappa(r, \pi - \Theta) U_{0\kappa} F_0(\mathbf{r})\, dr$ in (12) vanishes provided a symmetrical exchange interaction is assumed. For the states in which α does not vanish this term can be reduced readily to a straightforward double numerical integration over the coordinates r, u since

$$U_{0\kappa} = (8\pi M a^2 A/3\hbar^2) \int_0^\infty \chi_0(u) \chi_\kappa(u) B(u, r)\, du, \qquad \ldots\ldots(27)$$

where

$$\left.\begin{aligned} urB(u, r) &= \exp(-2r/a)\{(2r/a+1)\sinh(u/a) - (u/a)\cosh(u/a)\} \quad \text{if } r > u/2 \\ &= \exp(-u/a)\{(u/a+1)\sinh(2r/a) - (2r/a)\cosh(2r/a)\} \quad \text{if } r < u/2 \end{aligned}\right\} \qquad \ldots\ldots(28)$$

if the ejected neutron is in an s state, and

$$\left.\begin{aligned} urB(u, r) = {} & \exp(-2r/a)\{u/a + 2r/u + u/2r + 3a/u + 3a^2/2ur) \sinh(u/a) \\ & - (2r/a + 3 + 3a/2r)\cosh(u/a)\} \quad \text{if } r > u/2 \\ \text{and} \qquad \\ = {} & \exp(-u/a)\{(2r/a + 2r/u + u/2r + 3a/2r + 3a^2/2ur)\sinh(2r/a) \\ & - (u/a + 3 + 3a/u)\cosh(2r/a)\} \quad \text{if } r < u/2 \end{aligned}\right\} \qquad \ldots\ldots(29)$$

if the ejected neutron is in a p state.

§ 3. NUMERICAL CALCULATIONS

Calculations of the disintegration cross section have been carried out for incident neutrons of energy 4·14 MeV. ($k_0 = 0{\cdot}3$), 7·36 MeV. ($k_0 = 0{\cdot}4$), 11·5 MeV. ($k_0 = 0{\cdot}5$) and 16·56 MeV. ($k_0 = 0{\cdot}6$). The values of k_0 are expressed in units of $10^{13}\ \mathrm{cm}^{-1}$.

The calculations in the case $l = s = m = 0$ (ejected s neutron) were carried out exactly.

In addition the following cases might be expected to contribute appreciably to the cross section at higher energies:

$l = s = m = 1$ (ejected s neutron),
$l = 0,\ m = s = 1$ (ejected p neutron),
$l = s = 1,\ m = 0$ (ejected p neutron).

Since the calculations are very lengthy it was impracticable to carry them out accurately in all these cases. Instead, for these three cases the quantity

$$\left| \int \mathscr{F}_\kappa(r, \pi - \Theta) U_{0\kappa} F_0(\mathbf{r}_1)\, dr \right|^2$$

was calculated from equations (27), (28) and (29) for doublet states and $k_0=0{\cdot}5$ and compared with the corresponding term calculated for $l=s=m=0$. Actually, owing to the use of symmetrical forces the coefficient α of this term in (12) vanishes when the ejected neutron is in an s state, but it seems reasonable to expect that its variation with l,s,m would give an indication of the variation to be expected when the full expression for the cross section is used.

For the incident neutrons the radial wave functions $gm^i(k_0r)$ were available already for $k_0=0{\cdot}2$ and $0{\cdot}5$ (quartet) and $k_0=0{\cdot}2$ (doublet) from the calculations of Buckingham and Massey (1941) on n–d scattering. The doublet function for $k_0=0{\cdot}5$ $(m=0)$ was also calculated accurately. From these known functions doublet and quartet functions for $k_0=0{\cdot}3$, $0{\cdot}4$, $0{\cdot}6$ $(m=0,1)$ were obtained by interpolation or extrapolation. For given values of k_0, κ, the corresponding value of k' could be calculated from (16).

All the kernels q_0^{κ}, $p_0^{\kappa(1)}$, $p_0^{\kappa(2)}$, n_0^{κ} were computed for three values of κ, viz. 0·065, 0·1732, 0·3464, using accurately calculated s and p wave radial functions, $f_{0,1}(\kappa r)$ corresponding to the motion of the neutron in the neutron–proton field. Each of the integrations in equations (20) had to be carried out numerically for various points in the r, r' plane. Where necessary additional points were interpolated. Well over 1,000 integrations proved to be necessary. Owing to the presence of $\chi_\kappa(u)$ corresponding to the states of positive energy the kernels converge much less rapidly than in the n–d elastic scattering calculations and they are not uniform in sign. q_0^{κ} and $p_0^{\kappa(1)}$ are the dominant terms at short distances up to about 8×10^{-13} cm. At greater distances $p_0^{\kappa(2)}$ and n_0^{κ} are comparable and of opposite sign. As r,r' increase still further, n_0^{κ} becomes the largest term and it had to be calculated for distances as great as 30×10^{-13} cm.

Table 2. Relative Magnitude of various Terms contributing to the Amplitudes f^{Q}, f^{D}

	f^{Q}					f^{D}				
κ'	q	$p^{(1)}$	$p^{(2)}$	n	Total	q	$p^{(1)}$	$p^{(2)}$	n	Total
0·065	−0·214	−0·340	0·454	0·187	0·087	−0·370	0·018	−0·0243	0·053	−0·323
0·1732	−0·318	−0·713	1·071	0·139	0·179	−0·776	0·127	−0·0528	0·173	−0·529
0·3464	0·018	−1·180	1·403	−0·147	0·094	−1·351	−0·017	−0·1660	0·629	−0·900

On summing the kernels there is a great deal of cancellation and this reduces the accuracy of the result. Further cancellation occurs in the final integrations over r,r', especially at the lower energies. The cancellation renders the results rather sensitive to the various wave functions used. In general the kernels were summed before integrating over r and r', but in order to illustrate their relative importance the integrations were performed separately for $k_0=0{\cdot}5$. The relative importance of the various terms contributing to the amplitudes f^{Q}, f^{D} are shown in Table 2 for a number of different values of k'. In this table

$$\left.\begin{aligned}
q&=(\beta/4\pi)\iint Q_{0\kappa}(\mathbf{r},\mathbf{r}')F_0(\mathbf{r}')\mathscr{F}_\kappa(r,\pi-\Theta)\,d\mathbf{r}\,d\mathbf{r}',\\
p^{(1)}&=(\gamma/4\pi)\iint P_{0\kappa}^{(1)}(\mathbf{r},\mathbf{r}')F_0(\mathbf{r}')\mathscr{F}_\kappa(r,\pi-\Theta)\,d\mathbf{r}\,d\mathbf{r}',\\
p^{(2)}&=(\delta/4\pi)\iint P_{0\kappa}^{(2)}(\mathbf{r},\mathbf{r}')F_0(\mathbf{r}')\mathscr{F}_\kappa(r,\pi-\Theta)\,d\mathbf{r}\,d\mathbf{r}',\\
n&=(\epsilon/4\pi)(E_\kappa/E_0-4E_{k'}/3E_0-1/3)\iint N_{0\kappa}(\mathbf{r},\mathbf{r}')F_0(\mathbf{r}')\mathscr{F}_\kappa(r,\pi-\Theta)\,d\mathbf{r}\,d\mathbf{r}',
\end{aligned}\right\}\quad\ldots\ldots(30)$$

and the calculations refer to the case $l=s=m=0$. The amplitudes are expressed in arbitrary units. The cancellation is seen to be considerable, particularly for the quarter amplitude.

§ 4. RESULTS OF THE CALCULATION

The total disintegration cross sections calculated using equations (14) and (15) are shown in Table 3. To obtain those cross sections shown here the amplitudes have been calculated from equation (12) for the case $l=s=m=0$.

Table 3. Total Disintegration Cross Section (units 10^{-25} cm.)

Incident neutron energy (MEV.)	4·14 ($k_0=0·3$)	7·36 ($k_0=0·4$)	11·5 ($k_0=0·5$)	16·56 ($k_0=0·6$)
Cross section	0·22*	2·3*	6·4	16·0

The figures marked with an asterisk must be regarded as estimates only, since the cancellation was very severe in these cases.

The values given in Table 3 are lower limits of the calculated value of the cross section because they include only the contribution from the case $l=s=m=0$. As described earlier the contributions arising from other harmonics were estimated by calculating

$$(k'/k_0)\left|(4\pi)^{-1}\int \mathscr{F}_\kappa(r,\pi-\Theta)U_{0\kappa}F_0(\mathbf{r})\,d\mathbf{r}\right|^2 \qquad \ldots\ldots(31)$$

from (27), (28), (29) for the cases $l=s=m=0$; $l=s=m=1$, $l=0$, $m=s=1$, $l=s=1$, $m=0$ for the doublet state. The contributions to the cross sections calculated from equation (15) using expression (31) for $I(\theta,\phi,k')$ are shown in Table 4 for $k_0=0·5$ (doublet).

Table 4. Relative Importance of Different Harmonics in contributing to the Total Cross Section $k_0=0·5$ (doublet)

(Calculated by supposing $I(\theta,\phi,k')$ given by (31).)

l, m, s	0, 0, 0	1, 1, 1	0, 1, 1	1, 0, 1
Total cross section (units 10^{-25} cm^2)	7·5	0·01	0·16	$<0·001$

The total cross section given in Table 4 calculated using equations (14), (15) and (31) for the case $l=m=s=0$ ($7·5\times10^{-25}$ cm^2) is quite close to the corresponding quantity calculated using the full expressions (12), (14) and (15) and shown in Table 3 ($6·4\times10^{-25}$ cm^2). It is seen from Table 4 that the relative contributions from other harmonics is very small. It seems reasonable therefore to suppose that the contributions of the similar harmonics will be small also when the full expressions for the total cross sections are used.

§ 5. COMPARISON WITH PREVIOUS CALCULATIONS

The most extensive previous investigation of the n–d disintegration has been that of Höcker using a different formulation and a Gaussian well shape of interaction. Instead of an expression such as (12), Höcker (1942) took for the matrix element determining the cross section the quantity

$$\int \psi_{\mathrm{A}}\{V(u)+V(v)+V(t)\}\psi_\kappa\,d\mathbf{u}\,d\mathbf{r}, \qquad \ldots\ldots(32)$$

where $\psi_{\mathrm{A}}, \psi_\kappa$ are respectively the initial and final wave function. It is a little difficult to see the justification for taking the total interaction energy

$V(u)+V(v)+V(t)$ in the matrix element of (32). In an earlier investigation along similar lines Motz and Schwinger (1940) followed the more natural course of writing $V(v)+V(t)$ for the interaction energy in (32) and more recently this procedure has been followed by Wu and Ashkin (1948) in a formulation of the n–d disintegration problem at very high energies.

In Höcker's calculations $\psi_\Lambda, \psi_\kappa$ were calculated from the general equations (7) by an approximate method involving the expansion of F_0 in the form $N_f(1+\beta_2 r^2+\beta_4 r^4)\exp(-\alpha r^2)$ where $\alpha=0{\cdot}87$ and β_2, β_4 are quantities depending on the energy. The quantities β_2, β_4 were determined by a variation principle. This function was then joined to the asymptotic form $(\sin kr)/kr$ at an arbitrary distance r_0. The results depend somewhat on r_0, especially in the quartet case. Höcker's formulation is thus essentially a ' distorted wave ' theory. It differs from ours however in that the terms involving $P_{0\kappa}^{(2)}(\mathbf{r},\mathbf{r}')$, $N_{0\kappa}(\mathbf{r},\mathbf{r}')$ do not occur. It is evident from Table 2 that these terms have an important influence on the final result.

Over most of the range of neutron energies the cross sections calculated by Höcker are about three times as great as ours although the two sets of values agree more closely at lower energies.

Since the calculated cross sections come almost entirely from the $l=s=m=0$ case, it is possible to compare the calculated total cross section with the maximum possible value allowed by conservation theorems. If only the zero order partial wave is concerned in the scattering the maximum possible value for the total inelastic scattering cross section is π/k_0^2 (Mott and Massey 1949, p. 133). For $k_0=0{\cdot}5$ this maximum is $1{\cdot}26\times10^{-25}\,\mathrm{cm}^2$ under these conditions, i.e. the calculated value of the cross section is about five times as large as the maximum permitted by conservation laws. This result does not imply any error in the numerical calculations but indicates that the distorted wave method which has been used is inapplicable at these energies because the neutron–deuteron scattering must correspond to a case of strong interaction. The assumption that the function ϕ (23, 1) can be expressed in the form (8) and the neglect of $G_{\kappa0}$ in (10*b*) are thus unjustified. The position is precisely the same as for many inelastic cross sections calculated for the scattering of electrons by atoms and molecules (Bates, Fundaminsky, Leech and Massey 1950). It is interesting to note that the less accurate formulation of Höcker leads to a value of the cross section 15 times larger than the allowed maximum.*

In these circumstances it is very difficult indeed to say what the true theoretical cross section should be. Even in the case of electron collisions it has not proved possible so far to carry through accurate calculations of inelastic scattering cross sections in cases where the distorted wave approximation breaks down. Nor is it possible to ascribe limits to the error made in the use of the approximation. The position is even more complicated for nuclear scattering problems. An exact calculation is out of the question. Some light might perhaps be thrown on it from a study of the elastic scattering cross section at the same energy. For the partial cross section corresponding to s wave scattering for $k_0=0{\cdot}5$ the calculations of Buckingham and Massey (1941) give $4{\cdot}7\times10^{-25}\,\mathrm{cm}^2$. If the inelastic cross section were just equal to its maximum allowed value the corresponding partial elastic scattering cross section would be just equal to the inelastic cross section, i.e. $1{\cdot}26 \times 10^{-25}$ cm^2. It can probably be concluded from this that the true theoretical cross section for n–d disintegration should be appreciably less than the theoretical maximum.

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* For lower energy incident neutrons the calculated cross sections are smaller and the maximum permitted by the conservation laws greater, so that the calculated result would be expected to have more significance.

Owing to the strong interaction, contributions might be expected to the elastic cross section from double transitions of the type $0 \rightarrow \kappa$, $\kappa \rightarrow 0$ during the collision process. Such transitions have been shown to play an important part in the scattering of electrons by atoms under some circumstances (Massey and Mohr 1934). They would be expected to modify the angular distribution of the elastically scattered neutrons and to influence the total elastic scattering cross section, the effect being particularly marked above the threshold potential (about 3·3 MEV.) for disintegration.

§ 6. COMPARISON WITH EXPERIMENT

Very little experimental evidence is available about the magnitude of the n–d disintegration cross section. Such information as is available has been obtained in the course of investigations of n–d scattering by energetic neutrons. Ageno *et al.* (1947) estimated the cross section at 14 MEV. as $4\text{–}9 \times 10^{-26}$ cm^2 while Coon and Taschek (1949), using homogeneous neutrons of energy 14 MEV. from the T (d, n) ^{4}He reaction, obtained results which suggested a cross section of the order of 5×10^{-26} cm^2. The experimental cross sections are of an order of magnitude smaller than those calculated in this paper for fast neutrons but they are not inconsistent with the requirements of the conservation laws that the total cross section should not exceed π/k_0^2 so long as only s wave scattering is important.

At lower energies Barkas and White (1939) studied the disintegration of the deuteron by protons and estimated a cross section of $1{\cdot}4 \times 10^{-26}$ cm^2 for 5·1 MEV. protons. The calculated value for n–d disintegration by neutrons of this energy (admittedly rough) is 5×10^{-26} cm^2 which is well below the maximum prescribed by the conservation laws for this energy ($2{\cdot}8 \times 10^{-25}$ cm^2) and so should be significant. Assuming that the only difference between the p–d and n–d cases can be expressed in terms of a Gamow penetration factor the equivalent theoretical p–d cross section is about 3×10^{-26} cm^2. The agreement in this case is not unreasonable but underlines the need for further experimental study of these reactions.

ACKNOWLEDGMENTS

We are greatly indebted to Professor H. S. W. Massey for his interest in this problem and particularly for pointing out that the cross sections calculated at high energies by the distorted wave method violated the conservation laws. We are also indebted to him and to Dr. R. A. Buckingham for allowing us to use a number of radial wave functions calculated by them in their n–d elastic scattering investigation. We also wish to thank Miss K. Ledsham for considerable assistance in some of the computations.

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A Coincidence Absorption Study of the Decay of ^{181}Hf

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ABSTRACT. The decay of 46 day ^{181}Hf has been investigated by absorption coincidence techniques using an integral type delayed coincidence recorder, and a special counter with which the absorption curves of low energy electrons may be obtained.

The results confirm a previously published scheme for the main mode of decay, namely that a 400 kev. β-ray from ^{181}Hf leads directly to the 20 μsec. metastable state in ^{181}Ta. This decays by emission of a 130 kev. γ-ray, followed by a 470 kev. transition to the ground state. Instantaneous coincidences were found to involve the γ-transitions in the main branch, electrons from γ-rays of 87, 133 and 340 kev., and a β-ray of approximately 440 kev.

It is suggested that about 30% of the ^{181}Hf nuclei in the 46 day state decay by a highly forbidden γ-transition (133 kev.) with an 87 kev. γ-ray in cascade to the ground state. This decays through a 440 kev. β-transition to an excited state (340 kev.) of ^{181}Ta. Half life and conversion coefficient values enable spins and relative parities to be assigned to each of the levels occurring in the decay scheme proposed.

§ 1. INTRODUCTION AND SUMMARY

The 46 day activity in ^{181}Hf produced by slow neutron bombardment of hafnium has been studied by several workers since DeBenedetti and McGowan (1946) reported a metastable state in the resulting ^{181}Ta nucleus. Bunyan *et al.* (1948) reported the half life to be 20 μsec. and found that at least two γ-rays of approximately 130 and 470kev. are emitted in the decay from the metastable state. The lower energy ray is highly internally converted. Walker and Fuller (1949) have shown that the 400 kev. β-spectrum from hafnium is probably the only radiation preceding the metastable state.

Spectrographic investigations (Chu and Wiedenbeck 1949, Beneš *et al.* 1948) showed the presence of a 340 kev. γ-ray, and its conversion electrons, about one third as intense as the 470 kev. ray. Chu and Wiedenbeck (1949) resolved the K conversion electrons of the '130' kev. radiation into two peaks at 63 and 67 kev. indicating γ-ray energies of 130 and 134 kev., if both are converted in tantalum. Recently Jensen (1949) has found a photo-electron peak corresponding to an 87 kev. γ-ray which is probably not as intense as the 470 kev. radiation.

At the time the experiments reported below were carried out no coincidence measurements had been published which indicated where these other radiations occurred in the decay. However, some unpublished results obtained by M. Deutsch using one of the Stockholm spectrographs suggested that the 340 kev. γ-ray was not in the radiation following the metastable state.*

The author's results show that all the γ-rays mentioned give rise to instantaneous coincidences, and that only the 130 and 470 kev. γ-rays are present in the delayed radiation. One of the absorption curves obtained (Figure 5) provides evidence for the existence of a 440 kev. β-ray in coincidence with the 340 kev. γ-ray.

The decay scheme shown in Figure 6 and discussed in § 7 is consistent with most of the published information on this isotope.

§ 2. THE INTEGRAL RECORDER

A block diagram of the integral type delayed coincidence recorder (described by Bunyan *et al.* 1948) used in these experiments is shown in Figure 1. Every pulse from counter A is converted by the pulse lengthening circuit to an integrating pulse of length τ_A. If a pulse is formed in counter B at a time less than τ_A after a pulse in counter A, a coincidence will be registered. The anti-coincidence circuit rejects any coincidence occurring during an interval τ_D started by each pulse from counter A. As τ_D is made greater than the sum of the counter and circuit time lags, only delayed coincidences are recorded by scaler D, whereas both delayed and instantaneous coincidences are recorded by scaler C.

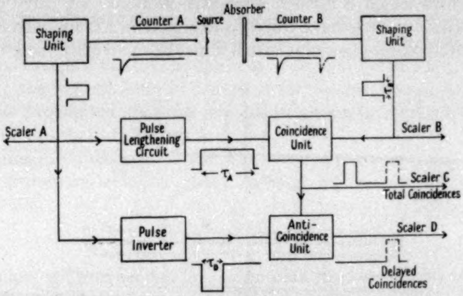

Figure 1. The integral recorder.
(as used for the absorption of delayed and instantaneous radiations.)

The integrating pulse length was set at 36 microseconds using a monitor with a calibrated time scale, the anti-coincidence pulse length being fixed at 1·8 microseconds. Both these pulse lengths were measured through random coincidences several times during the experiment, and were found to remain constant within the statistical accuracy of the measurements.

One advantage of this recorder is that the absorption of instantaneous coincidences may be studied simultaneously with the absorption of the preceding or delayed radiation.

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* This work was discussed by Professor Deutsch during his visit to this laboratory in 1948. I am indebted to him for permission to quote from it.

§ 3. COUNTERS

(i) *The Demountable Counter*

The demountable counter was built to investigate the absorption of the soft conversion electrons commonly emitted in isomeric transitions. Window absorption is eliminated by having two counters, the source, and absorbing foils in the same glass envelope which is filled with the counter gas mixture. The cathodes are cylinders of 0·1 mm. nickel sheet 1·5 cm. diameter, 10 cm. long, and the anodes are of 0·15 mm. tungsten wire, active length 5 cm. A glass bead approximately 2 mm. diameter is sealed on to the free end of each anode to prevent point discharges. The two counters lie on the same axis 1·5cm. apart, and the source, attached to a 2 mm. diameter tungsten rod which is sealed into a ground glass joint, can be inserted between them. With an argon–alcohol mixture (12% alcohol) at a pressure of 12 cm. Hg as the filling, the plateau characteristics were satisfactory and stable over a period of two months.

The aluminium absorbing foils are mounted on two brass wheels, 9·8 cm. in diameter, each of which is divided into seven sections: six carry foils and the other is left blank. One of these wheels is mounted on a 2 mm. diameter tungsten rod sealed into a ground-glass joint so that it may be rotated to change the absorber. The other is carried on a ⅛-inch diameter stainless steel rod which passes through a Wilson seal so that this wheel may be rotated and moved axially. Thus the two wheels may be separated whilst either is being rotated, and brought into contact again afterwards. The two sets of absorbers must be as nearly as possible in the same plane, since the shape of an absorption curve varies with the relative positions of the source, absorber and counter. The foils were chosen so that absorbers between 0 and 5 mg/cm^2 can be obtained in 0·2 mg/cm^2 steps and absorbers between 5 and 10 mg/cm^2 in 0·4 mg/cm^2 steps; the maximum absorber thickness obtainable is approximately 20 mg/cm^2. The source was placed on the axis of the two counters, 3 mm. from one, and 1 cm. from the absorber. The system was tested by taking absorption curves of the pure β-spectra of ^{35}S and ^{185}W; these were quite smooth and showed that a given absorber thickness formed by different combinations of foils had the same absorbing effect.

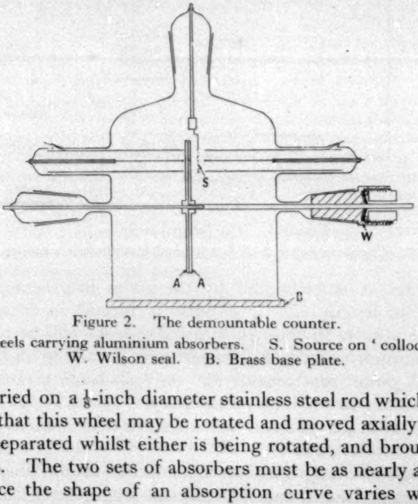

Figure 2. The demountable counter.
A, A. Wheels carrying aluminium absorbers. S. Source on 'collodion' film.
W. Wilson seal. B. Brass base plate.

(ii) *Other Counters*

G.E.C. end window counters types G.M.2 and G.M.4 were used to investigate the absorption of the harder radiations. The G.M.4's have a 7 mg/cm² dural window; thus absorption curves obtained with the demountable counter may be conveniently continued with these.

§4. THE METHOD OF COINCIDENCE-ABSORPTION

The general principles governing the analysis of the results of coincidence measurements have been given by Feather and Dunworth (1938) for instantaneous coincidences, and by Rotblat (1941), and Bunyan *et al.* (1949) for delayed coincidences. The particular results of these analyses used in the discussion of the author's results are given below.

(i) *Instantaneous Coincidences*

Suppose that two counters A and B detect rays 1, 2, ... *i*, ... *k* from a source which emits N_i rays of type *i* per second. Let *I* denote the ***group*** of rays which is in instantaneous coincidence with radiation *i*; *I* may be made up of any or all of the rays (except *i*) emitted by the source, depending on the mode of decay. Denote by ϵ_{Ai} the net efficiency of counter A for the detection of radiation *i* and let ϵ_{BI} be the probability that, for one disintegration in the source, counter B will detect one or other of the rays in *I*.

The genuine instantaneous coincidence rate due to the source (i.e. excluding random and cosmic coincidences) will then be given by:

$$C_{\text{inst}} = \sum_{i=1}^{k} N_i \epsilon_{Ai} \epsilon_{BI}. \qquad \ldots\ldots(1)$$

This relation, when expanded for the simplest case where only two radiations are in instantaneous coincidence, gives the familiar formula

$$C_{\text{inst}} = N(\epsilon_{A1}\epsilon_{B2} + \epsilon_{A2}\epsilon_{B1}).$$

Inserting absorbers between counter A and the source will reduce ϵ_A for all radiations; in particular, the efficiency for electrons of a given energy may be reduced to zero by adding absorber equal to the range corresponding to that energy. An end point will show in the coincidence absorption curve at this absorber value if these electrons are in coincidence with radiation sufficiently energetic to be detected by counter B. The change in slope at the end point will depend on the number of coincidences due to the radiation absorbed, and thus will be governed by the efficiency of counter B for the coincident radiations, as well as by the initial efficiency of counter A for the radiation itself.

Consider the case where two γ-rays and their internal conversion electrons are the only radiations producing coincidences. Assume that the internal conversion coefficients of the γ-rays and the γ-ray efficiencies of the counters are such that the unconverted γ-rays produce only a small fraction of the observed coincidence rate. If we denote the internal conversion coefficients $[N_e/(N_e + N_\gamma)]$ of the γ-rays γ_1 and γ_2 by α_1 and α_2 respectively, the electron–electron term in the expression for the genuine instantaneous coincidence rate at zero absorber thickness becomes

$$C_{\text{inst}(0)} = N\alpha_1\alpha_2(\epsilon_{Ae_1}\epsilon_{Be_2} + \epsilon_{Ae_2}\epsilon_{Be_1}), \qquad \ldots\ldots(2)$$

where N is the number of such transitions occurring in the source per second. Let γ_2 be the more energetic ray.

At zero absorber thickness the intrinsic efficiency of a Geiger counter for the detection of electrons is approximately unity so that $\epsilon_{Ae_1}=\epsilon_{Ae_2}$, and $\epsilon_{Be_1}=\epsilon_{Be_2}$. If we could absorb e_1 from the radiation entering counter A without absorbing e_2 at all, the coincidence rate would be reduced to half its initial value when e_1 was completely absorbed. In practice e_2 is also absorbed, but nevertheless the absorption curve should break so that the coincidence rate given by extrapolating the absorption of the harder component to zero absorber thickness is half the total rate. It can also be seen from this example that one cannot determine the relative conversion coefficients of the γ-rays concerned from the instantaneous coincidence absorption curve alone.

(ii) *Delayed Coincidences*

Suppose that the source placed between the counters decays through a metastable state of such a half-life that it may be detected with the integral recorder.

Let ϕ be the fraction of the counts occurring in counter A due to all the radiations (Preceding radiation) which lead directly or indirectly to the metastable state. Let ϵ_{Bd} be the sum of the net efficiencies of counter B for the detection of all the radiations (Delayed radiation) which follow the metastable state.

Any rays resulting from a mode of decay which does not pass through the metastable state constitute the Parallel radiation.

Denote the decay constant of the metastable state by λ, then the genuine delayed coincidence rate C_{del} is given by

$$C_{del}=\phi N_A \epsilon_{Bd} \exp(-\lambda\tau_D)[1-\exp\{-\lambda(\tau_A-\tau_D)\}] \qquad \ldots\ldots(3)$$

where N_A denotes the counting rate in counter A. The absorption curve of the preceding radiation is obtained by placing absorbers between the source and counter A, and plotting C_{del} against the absorber thickness, similarly the absorption of the delayed radiation may be studied by placing the absorbers in front of counter B. The relative values of the conversion coefficients of any γ-rays occurring in the preceding or delayed radiations can be estimated from these absorption curves. Their absolute values can be determined from the curves and equation (3) if the decay scheme is known.

§ 5. IRRADIATION AND PREPARATION OF THE SOURCES

A sample of Johnson, Matthey spectroscopically standardized hafnium oxide containing approximately 30% of zirconium oxide as the only important impurity was irradiated in the B.E.P.O. at Harwell for two months.

After irradiation the oxide was dissolved in a minimum of sulphuric acid; the sources were formed by evaporating this solution on a suitable backing. The source used in the demountable counter was evaporated on a collodion film, the total thickness of source and backing being less than 0·2 mg/cm². Aluminium foil (2·3 mg/cm²) formed the backing of the other sources.

According to the slow neutron cross sections given by Seren, Friedlander and Turkel (1947), approximately 0·7% of the activity was due to 65 day ^{95}Zr formed from the zirconium impurity.

§6. RESULTS

(i) *Preceding Radiation*

The absorption curve of the preceding radiation taken in the demountable counter was very similar to the absorption curve of the radiation from ^{185}W taken under the same geometrical conditions. This isotope is known to decay by β-emission only to the ground state of ^{185}Re; the β-transition, like that from ^{181}Hf, is once forbidden with $E_{\max}=400$ kev. As tungsten and hafnium have approximately the same atomic number, it is reasonable to assume that the similarity of the two absorption curves indicates that the only radiation preceding the metastable state is the 400 kev. β-spectrum from 46 day ^{181}Hf. In particular, there was no evidence of a soft electron radiation which could have escaped detection in previous investigations.

(ii) *Delayed Radiation*

Curve A of Figure 3 is the absorption curve of the low energy electrons occurring in the delayed radiation. The end point of the softest component corresponds to an energy of 64 kev., agreeing well with the value expected for electrons from a 130 kev. γ-ray converted in the K shell of tantalum. The absorption of the harder delayed radiation is shown by curve A of Figure 4. G.M.4's were used as detectors for this part of the experiment, the source being 1 cm. from counter B (delayed radiation) so that a correction of 8·5 mg/cm^2 should be added to the absorber values on this figure. The end point at

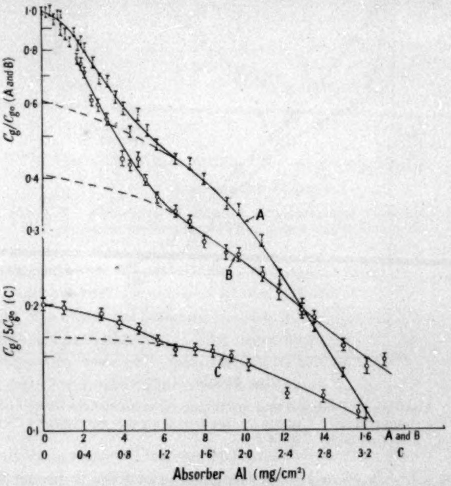

Figure 3. Absorption of delayed and instantaneous coincidences in the demountable counter. (Semi-logarithmic plot)

A : Delayed radiation. B, C : Instantaneous radiation. C_{g0} = Genuine delayed (A) or instantaneous (B) coincidence rate at zero added absorber thickness. C_g = Genuine coincidence rate at corresponding absorber thickness. The r.m.s. error is shown on the points for the curves in this Figure and Figures 4 and 5.

14 mg/cm^2 added absorber thus corresponds to an electron of approximately 130 kev. (L and M conversion of a 130 kev. γ-ray). A large number of points was taken to determine the shape of the part of the curve following this break. The increase of slope with increasing absorber thickness indicates the absorption of a homogeneous electron line, the end point of which corresponds to K conversion of the 470 kev. γ-ray. The relatively small number of electrons arising from conversion of this ray in the L shell does not distort the curve appreciably but gives a separate end point at 162 mg/cm^2 total absorber again corresponding to 470 kev.

(iii) *Instantaneous Radiations*

The absorption characteristics of the radiations causing instantaneous coincidences are shown in Figure 3 curves B and C, Figure 4 curve B, and Figure 5. Curve B of Figure 3 was obtained simultaneously with the corresponding curve A using the demountable counter. As well as the end point due to the K electrons from the 130 kev. radiation there is an end point at 1·1 mg/cm^2 which corresponds to an electron energy of 24 kev. This is shown on an extended absorber scale in curve C. This electron may be interpreted as arising from K conversion of the 87 kev. line observed by Jensen (1949). The change in slope at the end point due to the 64 kev. electron is much greater in curve B of Figure 3 than it is in curve A, indicating that the value of the ratio of 64 to 130 kev. electrons is higher in the instantaneous radiations than it is in the delayed.

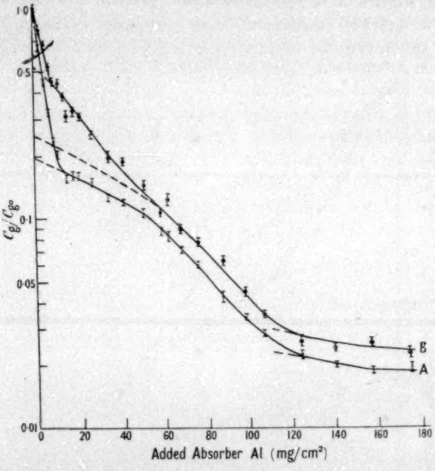

Figure 4. Absorption of delayed and instantaneous coincidences using G.M.4 counters (semi-logarithmic plot). Window thickness and air gap equivalent to 8·5 mg/cm^2 Al. C_{g0} and C_g defined under Figure 3.

Curve B of Figure 4, showing the absorption of instantaneous coincidences using G.M.4 counters, was taken at the same time as curve A. The end points in curve B can be assigned to electrons from L and M conversion of the 130 kev.

ray and K conversion of the 470 kev. ray. However, the shape of this curve between these two end points is significantly different from that of curve A over the same region.

Figure 5 represents the absorption of radiations which are in instantaneous coincidence with electrons harder than 130 kev. To obtain this, 25 mg/cm^2 of aluminium (including window thickness) were interposed between the source and one counter, and variable absorbers were placed in front of the other. For this experiment G.M.2 counters with 20 mg/cm^2 dural windows were used. Under these conditions it was convenient to use a strong source so an instantaneous coincidence circuit of 0·4 μsec. resolving time was used instead of the integral recorder. If there are only two electron components harder than 130 kev. in coincidence with each other, the first break should occur so that, after subtracting the coincidences due to γ-rays, the harder component extrapolates back to half the initial value. If this is the case the best fit with the observed points is obtained by drawing the curve so that the first end point is at 70 mg/cm^2 total absorber which corresponds to a 270 kev. electron. The other end point at 145 mg/cm^2 indicates an electron energy of 440 kev. Reasons for believing that we are here dealing with a simple two-component coincidence are given in the next section.

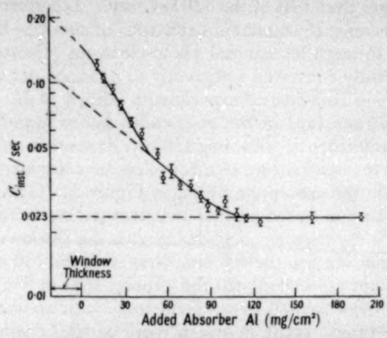

Figure 5. Absorption of radiation in instantaneous coincidence with electrons harder than 135 kev. (semi-logarithmic plot).

§7. DISCUSSION

Previous investigations (DeBenedetti and McGowan 1946, Bunyan *et al.* 1948) have shown that a 400 kev. β-ray precedes the 20 μsec. metastable state in ^{181}Ta: the author's results support the view that this is the only preceding radiation. Bethe's (1937) formula for the half lives of γ-ray transitions, and the conversion coefficients in the tables circulated by Rose *et al.* (1949) both suggest that the highly converted 130 kev. γ-ray is emitted by the metastable nucleus, the transition being three times forbidden. Conversion electrons of the 470 kev. γ-ray also appear in the delayed radiation so the 130 kev. transition cannot lead directly to the ground state of ^{181}Ta. The fact that these two radiations also give rise to instantaneous coincidences suggests that they are in cascade. As the conversion electrons of the 470 kev. γ-ray constitute the hardest electron component in both the delayed and instantaneous radiations, the high energy parts of the two absorption curves should be parallel. Figure 4 shows that they are parallel only at absorber thicknesses greater than 70 mg/cm^2. This may be interpreted as evidence for the presence of a 270 kev. electron (end point 70 mg/cm^2) in the radiation giving instantaneous coincidences which is not present in the delayed radiation. K conversion of a 340 kev. γ-ray would give an electron of this energy.

The observed number of delayed electrons per electron counted, taken in conjunction with values for the total conversion of the 130 and 133 kev. γ-rays obtained with β-ray spectrographs (Chu and Wiedenbeck 1949), indicates that only one of these rays (130 kev.) is present in the delayed radiation. The explanation of the fact that the ratio of 64 to 130 kev. electrons is greater in the instantaneous radiation than in the delayed may therefore be that the 133 kev. transition gives instantaneous coincidences, and the ratio of K to L conversion of this γ-ray is larger than that of the 130 kev. ray. L conversion of the 87 kev. γ-ray would also increase the number of electrons of about 64 kev. but, as this ray was first detected through its external photo-electrons (ejected from lead), it is probably not internally converted sufficiently to produce the observed effect.

Instantaneous γ–γ coincidence experiments (Beneš *et al.* 1948) have shown that the 340 and 470 kev. rays are not in cascade; hence the 470 kev. transition is in instantaneous coincidence with the 130 kev. transition only. Therefore it could not give rise to instantaneous electron–electron coincidences in the arrangement used to obtain the absorption curve in Figure 5. Thus the end point at 145 mg/cm^2 must be due to some other radiation giving 440 kev. electrons, this radiation being in instantaneous coincidence with the 340 kev. transition.

These results indicate that the 400 kev. β-ray, and the 130 and 470 kev. γ-rays are the only radiations associated with the 20 μsec. state in ^{181}Ta, and that the 87, 133 and 340 kev. γ-rays, as well as some electrons with an absorption end point corresponding to 440 kev. occur in one or more parallel chains. If we suppose these electrons to be β-rays with $E_{\max} = 440$ kev., these two groups of rays have the same total energy (1,000 kev.). This suggests that there is only one parallel mode of decay with all the radiations in it in direct cascade and therefore of the same intensity. The relative intensities of the 340 and 470 kev. γ-rays have been measured by Chu and Wiedenbeck (1949) whose results indicate that approximately 70% of the ^{181}Hf nuclei decay through the 20 μsec. metastable state. This means that the conversion of the 133 kev. γ-ray which, according to the above author, gives 0·22 K-conversion electrons per β-particle, must be almost 100%, implying that the transition is even more highly forbidden than that from the 20 μsec. state. The decay scheme shown in Figure 6 requires that this transition is five times forbidden. Bethe's formula corrected for internal conversion predicts a half life (10 yr.) about twenty times longer than that which would give 30% in this branch (180 day), but the derivation of this formula is such that agreement within a factor of one hundred is considered satisfactory.

Figure 6 represents the simplest mode of decay which will explain all the coincidence measurements reported here. The sequence of the radiations composing the 30% branch is deduced from the following considerations. The 133 kev. γ-transition is from a long-lived state and yet it gives rise to instantaneous coincidences; this means that it leads to a short-lived state which may decay by either the 87 or the 340 kev. γ-transition. However, it has been shown that the 340 kev. γ-ray is in instantaneous coincidence with a β-transition of 440 kev. which will have a half-life of many seconds at least. The 340 kev. γ-ray cannot give instantaneous coincidences with two slow transitions; thus it must be the 87 kev. transition which is responsible for the instantaneous coincidences given by the 133 kev. γ-ray. The experimental evidence presented here is not sufficient to decide whether the branching at the 46 day state of ^{181}Hf is between the 400 kev. β-transition (once forbidden) and the 133 kev. γ-transition (five times forbidden), or between the two β-transitions. However, as the 133 kev. γ-transition is highly forbidden, one encounters difficulties in assigning spins to the levels occurring in any scheme which assumes that the branching is between the two β-transitions. For this reason it has been assumed that the 133 kev. γ-ray is the first radiation emitted in the subsidiary branch. The scheme constructed on this assumption suggests that the 440 kev. β-transition is allowed and may therefore be connected with the 5·7 hour β-activity in hafnium reported by Muelhause (1949).

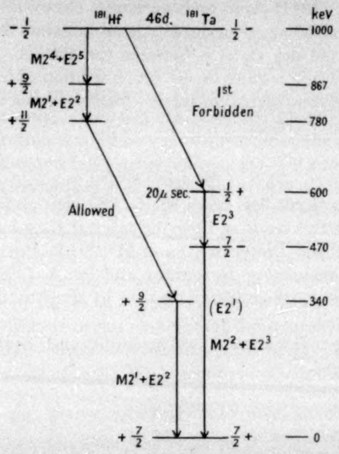

Figure 6. The decay scheme of ^{181}Hf.

An electric multipole transition of order n is indicated by $E2^n$; $M2^n$ denotes a magnetic 2^n pole transition. The relative parity is shown by + or −. Energies are given in kev.

The spin of the ground state of ^{181}Ta has been found to be 7/2 by McMillan and Grace (1933). The spins and relative parities of the other states were chosen so that the observed conversion coefficients of the γ-ray transitions between those states should agree with the theoretical values given by Rose *et al.* Also they are consistent with the fact that the 400 kev. β-ray results from a first forbidden transition if the Gamow–Teller selection rules apply.

To explain the absence of a 600 kev. cross-over transition in the main branch it must be assumed that such a transition would be at least four times forbidden. The present scheme satisfies this requirement, without postulating a very high spin for the 600 kev. level, but allows the 470 kev. transition to be an electric dipole ($E2^1$) although the conversion coefficients indicate that this transition is two or three times forbidden. Bethe (1937) has pointed out that electric dipole transitions are usually forbidden by symmetry properties of the nucleus so that they are no more probable than once forbidden transitions. In this case electric quadrupole ($E2^2$) and magnetic dipole ($M2^1$) transitions are forbidden by parity. It may be that the dipole moment for this transition is so small that a fraction of the transitions sufficient to give the observed conversion coefficients and transition probability are electric octopole ($E2^3$) or magnetic quadrupole ($M2^2$).

Barber (1950) has recently reported a $1{\cdot}1 \times 10^{-8}$ second state in ^{181}Ta which may be attributed to the 470 kev. level; this half-life agrees well with that predicted by the Bethe formula if the transition is three times forbidden. Also the results of an attempt by Professor P. B. Moon to measure the width of the 470 kev. level by a resonance scattering method suggest that this level is narrower, and therefore of longer life-time, than one would expect if the transition were electric quadrupole ($E2^2$).

Burson and Blair (1949) claim to have found electrons from the 340 kev. γ-ray in the delayed radiation; their decay scheme suggests that the branching in the *hafnium* nucleus (46 day state) is between the 400 kev. β- and the 87 kev. γ-transitions. This would require the 87 kev. transition to be at least four times forbidden, which implies so high a conversion coefficient that it is unlikely that the γ-ray could have been observed.

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On the Development of the Nucleon Component of the Cosmic Radiation in Air

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ABSTRACT. The development of the nucleon component in air is considered in terms of a model which is an extension of that proposed by Heitler and Jánossy. The numerical results obtained are compared with experiment, and good agreement is found.

§ 1. INTRODUCTION

In recent years it has become increasingly evident that the development of the nucleon component of the cosmic radiation must be described in terms of some cascade process. This fact has been clearly brought out both by direct experiments and by indirect experiments, such as those on the variation with altitude and latitude of the slow and fast neutron component of the cosmic radiation and of the star component (Bernardini *et al.* 1949, Simpson *et al.* 1948, 1949, 1950). A theory for such a process was suggested tentatively by Heitler and Jánossy (1949) and applied to the high energy region (energies above 5×10^9 ev.). It was found that the high energy phenomena could be satisfactorily described in these terms. An interesting feature of the above work was the insensitivity of the results to the detailed mechanism of the model used. We have accordingly felt justified in investigating the application of this model to the interpretation of the experimental results on low energy nucleons. Mathematical investigation of the nucleon cascade was given by one of us (H.M.) recently.

§ 2. FORMULATION OF THE MODEL

Although little is known about the cross sections for nuclear processes with energies in excess of 2×10^8 ev., the following features of such processes are currently assumed:

(*a*) The basic process of energy loss takes place in individual nucleon–nucleon collisions each of which leads to the production of one secondary nucleon. In addition such processes will lead to meson production in a fraction of the cases in the energy range 2×10^8 to 2×10^9 ev., and in the majority of cases above 2×10^9 ev.

(*b*) The cross section for nucleon–nucleon interactions is known experimentally to fall off with roughly a $1/E$ dependence (E is the energy) up to energies of the order of 2×10^8 ev. Theoretically it is thought that the cross section will continue to decrease until processes of meson production become important, and it will then rise again to roughly the geometrical cross section. Extrapolation of present experimental values for the interaction cross section leads to an absorption mean free path for 2×10^8 ev. neutrons of the order of 130 gm/cm^2 in air. The absorption mean free path for nucleons in the 10^9 ev. range is also roughly 130 gm/cm^2. From cosmic-ray experiments an absorption mean free path of 135 gm/cm^2 in air is obtained for the nucleon component at sea level. If the nucleons in the range of energies 2×10^8 to 2×10^9 ev. had a substantially lower absorption mean free path, such nucleons would tend to predominate in the nucleon component at sea level, and this would then have an absorption mean free path greater than the observed one of 135 gm/cm^2 in air. It seems, therefore, that the increase in the cross section for meson production at energies above 2×10^8 ev. counterbalances the decrease in the cross section for elastic collisions, the absorption mean free path thus remaining constant.

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(*c*) The interaction mean free path for nucleons with nuclei is roughly geometrical. Experimental justification for this is provided by the Berkeley experiments for nucleons with energies up to 3×10^8 ev., by the Bristol group experiments for nucleons with energies up to 10^9 ev., and from penetrating shower experiments for energies in the 10^9 ev. range.

Accordingly the main features which must be incorporated in a theory of the absorption of the nucleon component would appear to be a multiplication ratio of 2, i.e. every nucleon–nucleon interaction giving rise to a secondary nucleon, a constant absorption mean free path of 130 gm/cm^2, and a constant interaction mean free path of 65 gm/cm^2 in air.

The cross section adopted below incorporates the necessary features outlined above. The cross section is defined as follows. In a process in which a nucleon of energy E_0 loses energy, and also gives rise to a recoil nucleon, it is assumed that the probability for a collision to occur is given by

$$w(E_0\,;E_1,E_2)\,dE_1\,dE_2 = w\left(\frac{E_1}{E_0},\frac{E_2}{E_0}\right)\frac{dE_1\,dE_2}{E_0{}^2} = \sigma\epsilon_2{}^{\beta}(1-\epsilon_1)^{\nu}\,d\epsilon_1\,d\epsilon_2 \quad \ldots\ldots(1)$$

where we have taken $\epsilon_i = E_i/E_0$ with $i = 1,\ 2,\ w(\epsilon_1, \epsilon_2) = \sigma\,\beta\epsilon_2{}^{\beta}(1-\epsilon_1)^{\nu}$ and $\sigma = 15$, $\beta = 2$ and $\nu = 1$. The above cross section was suggested tentatively by Heitler and Jánossy (1949) and investigated analytically by Messel (1950). This model gives a loss of energy out of the nucleon component. (At high energies this energy will appear predominantly as mesons, and at energies of 10^8 ev. partly as mesons and partly as ionization losses. At lower energies the ionization losses are too large to be covered by this term, and it will be in this sense that we shall talk of solutions neglecting ionization losses.)

§ 3. EVALUATION AND NUMERICAL RESULTS

Neglecting ionization losses, the methods of solution of a cascade of the above type have been given in full previously (Heitler and Jánossy 1949, Jánossy 1950, Messel 1950, Jánossy and Messel 1950). We are interested physically in solutions for nucleons with energies of the order of 10^8 ev. For nucleons with energies of the order of 10^8 ev. the rate of loss of energy by ionization will be of the same order as that in nuclear collision processes, and thus the neglect of ionization losses is not justified.

In analogy with the similar problem encountered for the low energies in the electron–photon cascade, we shall make the approximation that the number of nucleons above 10^8 ev. is given by the formula neglecting ionization loss, in which the limit of 10^8 ev. is replaced by (10^8 ev. $+ E_0$). In the electron–photon cascade E_0 is roughly the energy loss by ionization per cascade length. (Note that in this approximation we do not attempt to differentiate between numbers of protons and neutrons. It is obvious that low energy protons will be preferentially removed from the cascade.)

The comparisons which we shall make with experiment are insensitive to the choice of minimum energy and, therefore, we do not consider that the large uncertainties inherent in the above approximation are serious.

The results of the papers quoted previously give for the number of particles $N(E/E_c, \theta)$ with energies greater than E at a depth θ in inhomogeneous matter, that is, matter in which the nucleons are grouped in nuclei.

$$N\left(\frac{E}{E_c}, \theta\right) = \frac{1}{2\pi i}\int_{s_0-i\infty}^{s_0+i\infty}\left(\frac{E}{E_c}\right)^{-s}\frac{\gamma}{s(\gamma-s)}\exp-\theta f(d_A\alpha_s)\,ds \qquad \gamma>s_0 \quad \ldots\ldots(2)$$

with

$$N\left(\frac{E}{E_c}, 0\right) = \begin{cases}\left(\dfrac{E}{E_c}\right)^{-\gamma} & E>E_c \\ 1 & E<E_c\end{cases} \quad \ldots\ldots(3)$$

E_c is the cut-off energy and $\gamma = 1{\cdot}7$.

$$\alpha_s = \int_0^\infty\int_0^\infty (1-\epsilon_1{}^s-\epsilon_2{}^s)\,w(\epsilon_1,\epsilon_2)\,d\epsilon_1 d\epsilon_2 \quad \ldots\ldots(4)$$

$$f(t) = 1 - 2\,\frac{1-(1+t)e^{-t}}{t^2}, \quad \ldots\ldots(5)$$

and d_A is the average number of collisions which a nucleon suffers along a nuclear diameter.

If we denote the range of nuclear forces by R_k, then d_A is given by

$$d_A = 1{\cdot}5A^{1/3}\left\{\frac{R_k}{1{\cdot}37\times10^{-13}}\right\}^2, \quad \ldots\ldots(6)$$

with A the atomic weight.

For air d_A was taken to be equal to 2·41. The depth θ is actually $\theta = \bar{\theta} n\Phi_A$, where $\bar{\theta}$ is the depth in gm/cm^2 and $n\Phi_A$ is the reciprocal cross section. We have evaluated curves giving the numbers of nucleons with energies above 10^8 and 2×10^9 ev. for the incident power law spectrum given above. We chose values of the cut-off energy E_c of 2×19^9 ev. and 15×10^9 ev. respectively, corresponding roughly to the latitude cut-offs for northern latitude, and the geomagnetic equator.

The 10^8 ev. curve is calculated from the above formulae using a value of E equal to $2{\cdot}66\times10^8$ ev. To approximate the effects of ionization loss this value should be $2{\cdot}3\times10^8$ ev. from the considerations given above. However, the use of a value of $2{\cdot}66\times10^8$ ev. which bears the same ratio to 2×10^9 ev. as does 2×10^9 ev. to 15×10^9 ev. saves a considerable amount of computation, without appreciably changing the results.

The experiments with which we shall compare the above data are all of a 'non-directional' variety, and accordingly it is necessary to apply an inverse Gross transformation integrating over all directions of incidence. The results are given in Figures 1 and 2.

§ 4. COMPARISON OF RESULTS WITH EXPERIMENT

The results can be compared with the altitude and latitude dependence of the slow and fast neutron component, of the star component, and the burst-producing component. We shall discuss each of these in turn.

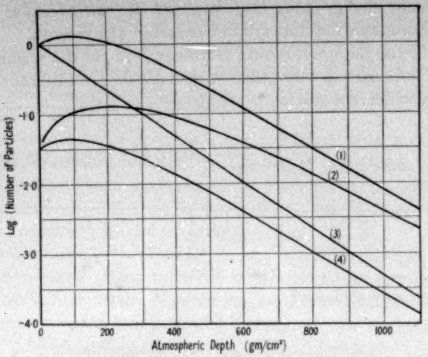

Figure 1. Plot of the logarithm of the vertical intensity of particles with energies greater than E due to a primary power law spectrum given by (3), against atmospheric depth in gm/cm².

(1) $E=10^8$ ev., $E_c=2\times10^9$ ev., the cut-off energy at ' northern latitudes '.
(2) $E=10^8$ ev., $E_c=15\times10^9$ ev., the cut-off energy at the geomagnetic equator.
(3) $E=2\times10^9$ ev., $E_c=2\times10^9$ ev.
(4) $E=2\times10^9$ ev., $E_c=15\times10^9$ ev.

The curves are normalized to an intensity of one at northern latitudes and to log $(2/15)^{1\cdot7}$ at the geomagnetic equator.

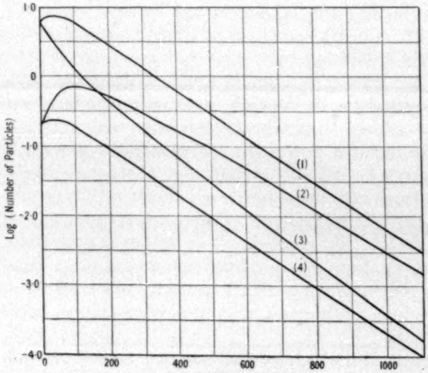

Figure 2. Plot of the logarithm of the total intensity with energies greater than E due to a primary power law spectrum given by (3), against atmospheric depth in gm/cm².

(1) $E=10^8$ ev., $E_c=2\times10^9$ ev.
(2) $E=10^8$ ev., $E_c=15\times10^9$ ev.
(3) $E=2\times10^9$ ev., $E_c=2\times10^9$ ev.
(4) $E=2\times10^9$ ev., $E_c=15\times10^9$ ev.

The curves are normalized to an intensity of log 2π at northern latitudes and to log $2\pi\,(2/15)^{1\cdot7}$ at the geomagnetic equator.

(*a*) *Altitude Dependence of Bursts, Photographic Plate Stars and Slow and Fast Neutrons.*

The close connection between the bursts observed in an ionization chamber and the star production observed in a photographic plate has been adequately discussed by Rossi and Williams (1947), and it is clear that the phenomenon being observed is almost certainly the same in both cases.

The question of the production of stars and neutrons has been widely discussed by many authors, and from these it would appear that the following views are probably correct.

(i) The excitation energy necessary for the production of a star with three or more prongs is generally greater than 10^8 ev. This corresponds to our lower limit of 10^8 ev. for nucleons.

(ii) The model we have outlined is not valid for nucleon energies below 10^8 ev., due both to the rapid rise in cross section and to the fact that such nucleons are produced predominantly by evaporation from excited nuclei. Due to the origin in excited nuclei, the number of such nucleons will, however, be directly related to the intensity of the star component at an equivalent altitude. (The interpretation at the highest altitudes is complicated by the fact that nucleons are emitted isotropically in ' evaporation ' processes, and that the resultant slow neutrons arising from this flux can further diffuse a considerable distance through the atmosphere. This leads, as is well known, to the occurrence, both theoretically and experimentally, of a maximum in intensity of the neutron component, which has no connection with the cascade maximum suggested by our model.)

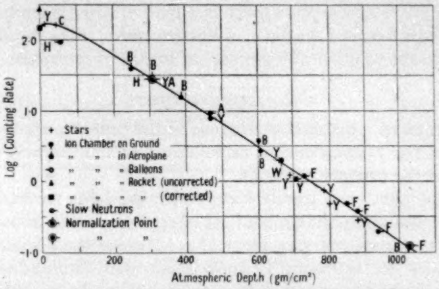

Figure 3. Theoretical curve obtained by us and the experimental results normalized by Rossi. Points from star data by Camerini *et al.* and Yagoda have also been added. The theoretical curve has been normalized to agree with the data at 650 gm/cm².

A, Agnew *et al.*; B, Bridge; W, Williams; H, Hulsizer;
Y, Yuan *et al.*; F, Fünfer; +Y, Yagoda; C, Camerini *et al.*

In Figure 3 we have transcribed collected experimental results for bursts and neutron intensities given in the Rossi review article (1948) for variation in intensity throughout the atmosphere, and have normalized our theoretical curve to give agreement at 650 gm/cm² depth. We have in addition added later photographic plate data on stars of Yagoda (1949) and Camerini *et al.* (1949). The results of Bernardini *et al.* (1948, 1949) are represented accurately by an exponential absorption between sea level and 25,000 metres with a mean free path of

135 ± 4 gm/cm^2, in excellent agreement with the results of the two authors mentioned above. As far as can be judged, the change in intensity with atmospheric depth of these results is represented accurately by our theoretical curve. (It was pointed out by Rossi (1948) that these results could in no way be fitted by an inverse Gross transform of an exponential, and it was suggested that this deviation was due to some type of transition effect at the top of the atmosphere.)

It is not possible to state from the observed experimental data whether or not the small maximum at 20 gm/cm^2 depth actually occurs. In this connection we note from Figure 2, curve 2, the very much more marked maximum that should occur at the geomagnetic equator.

Another interesting feature shown in Figure 2, curve 2, is the departure of the curve from exponential behaviour down to depths of several hundred grammes. Systematic measurements made on slow and fast neutron intensities and burst production by Simpson *et al.* (1948, 1949, 1950) at the geomagnetic equator do in fact show such an effect. These measurements at atmospheric depths between 200 and 400 gm/cm^2 give an absorption mean free path of 210 ± 8 gm/cm^2, whereas the slope expected from Figure 2, curve 2, is 200 gm/cm^2. This should be compared with the much lower value of 135 gm/cm^2 at northern latitudes.

(*b*) *Latitude Effect*

We have not given a detailed evaluation of the latitude effect, as it would be necessary to use the rather detailed calculations of the allowed energies at the various angles of the primary radiation.

In view of the paucity of the data at present available we have considered it sufficient to use the approximation of all energies allowed above 2×10^9 ev. at northern latitudes and all energies above 15×10^9 ev. at the geomagnetic equator. Our model shows an increasing latitude effect with increasing altitude. At 30,000 ft. the predicted latitude effect for neutrons above $2{\cdot}66 \times 10^8$ ev. is 5·0. The observed value is 3·5. The predicted value at 550 gm/cm^2 depth is, according to photographic plate measurements of Yagoda (1949), of the order of 3·5, whereas the theoretical value obtained by us is 3·0. In view of the approximation we have had to make for the incident primary spectrum at the geomagnetic equator and the uncertainty of the factor 1·7 occurring in the power law spectrum, we consider the agreement with our model as satisfactory.

(*c*) *Change of Star Type with Height*

Recent work (Camerini *et al.* 1949, Salant *et al.* 1948, Yagoda 1949) has made it certain that there is a slow but definite change in the star prong distribution between balloon altitudes and sea level. At sea level there is an increase in the proportion of small stars and a decrease by a factor of 2 in the proportion of ‘ hard ’ stars (Brown *et al.* 1949, Camerini *et al.* 1949), i.e. stars associated with the production of particles with minimum ionization. The most complete data at present available are those of Camerini *et al.* (1949) at 70,000 ft. A significant feature of these data is the high proportion (three-quarters) of stars due to neutral primaries and of small stars not associated with the production of minimum ionization particles. This is in qualitative agreement with our model, which predicts a very rapid increase of secondaries in the range 10^8 to 2×10^9 ev. From Figure 2, curves 1 and 3, it is seen that at 70,000 ft. already two-thirds of the nucleons with energies above 10^8 ev. are in the range 10^8 to 2×10^9 ev. This ratio has increased to the order of nine-tenths at 3,000 metres, a change which might well account for the observed experimental differences. Assuming that only one-tenth of the particles with energies between 10^8 and 2×10^9 ev. are capable of forming 'hard' stars (corresponding to a cross section for meson production of the order of 10^{-27} cm^2), and that one half of the particles with energies above 2×10^9 ev. are capable of forming such stars, we can in fact account quantitatively for the change observed.

For interest we have plotted in Figure 4, using the above results, values calculated for the change in the ratio of 'hard' stars to total star population with variation in altitude for both northern latitude and the geomagnetic equator. Theoretically there should be practically no difference between these ratios in passing from northern latitudes to the geomagnetic equator, even up to the highest altitudes obtainable in balloon flights. This is due to the rapid rate at which equilibrium is established between the low and high energy nucleons. No data are at present available on these points, and confirmation would be of interest.

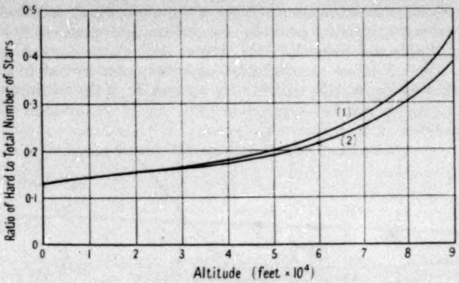

Figure 4. The ratio of the number of 'hard' stars to the total number of stars plotted against the altitude, in feet, for cut-off energies: (1) 15×10^9 ev., (2) 2×10^9 ev.

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Simpson, J. A., and Uretz, R. B., 1949, *Phys Rev.*, **76**, 569.

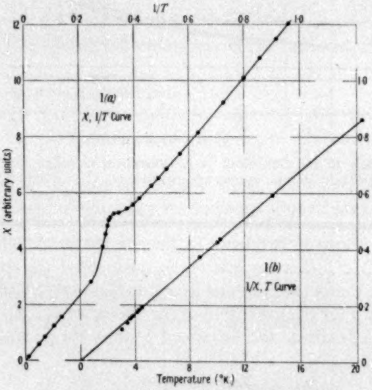
Yagoda, H., 1949, *Proc. Echo Lake Conference*, p. 169.

LETTERS TO THE EDITOR

The Magnetic Susceptibility of Copper Caesium Sulphate

Paramagnetic alums and Tutton salts are established as being in general suitable for very low temperature work, including the attainment of temperatures below 1° K. by adiabatic demagnetization, since they obey Curie's law or a Curie–Weiss law down to extremely low temperatures. During work on hydrated double sulphates of copper we have found that while the ammonium, potassium and rubidium salts are well-behaved paramagnetics down at least to 1° K., the susceptibility of copper caesium sulphate increases sharply between 4° and 3·1° K. and exhibits remanence below 3·1° K. This unusual behaviour is the more surprising in that specific heat measurements (Benzie and Cooke 1949) indicate that interaction between the ions is weaker in this salt than in the other three.

Measurements were made on a powdered sample at temperatures from 20° to 8° K. and from 4·2° to 1° K. The experimental method has already been described (Benzie and Cooke 1950). Measurements of susceptibility were made by an A.C. mutual inductance method, and remanence measurements by the ballistic galvanometer technique devised by Kurti, Lainé, Rollin and Simon (1936). Figure 1(*a*) shows a graph of susceptibility χ against $1/T$. Above 4° K. the susceptibility is inversely proportional to the temperature. This is emphasized by Figure 1(*b*), showing $1/\chi$ against T; if the salt is assumed to follow a Curie–Weiss law, $\chi = C/(T-\Delta)$, then Δ is certainly less than 0·05°. The susceptibility increases rapidly from 4° to 3·1° K., and below 2° K. it increases approximately as $1/T$ with roughly the same constant of proportionality as at higher temperatures. Hysteresis and the typical ferromagnetic (I, H) relation were indicated by the A.C. measurements at 3·5° K. and below. As the measuring field was increased from 0·4 oersted (r.m.s.) to 4 oersted the susceptibility increased by over 1%, but at 20 oersted had fallen by nearly 3%. At the same time a component of magnetization out of phase with the magnetic field was detected. (At temperatures where hysteresis occurred a very small measuring field was used for the susceptibility measurements, so that it was very nearly the reversible susceptibility that was measured.) Remanence was detected by the ballistic galvanometer method at 3·09° K. and below. The remanence, expressed as a percentage of the total magnetization in a field of 40 oersted, was as follows :



The susceptibility of copper caesium sulphate.

Temperature (°K.)	3·09	2·85	2·59	2·17	1·35	1·04
Remanence (%)	2·5	4	5	6·5	5	4

Previous reports of phenomena of this kind concern either anhydrous salts or else extremely low temperatures. Workers at Leiden (de Haas and Schultz 1939, de Haas, Schultz and Koolhaus 1940) have found that many anhydrous salts of the iron group show field dependence of the susceptibility and in some cases remanence at liquid hydrogen temperatures. In these anhydrous salts, however, exchange coupling between the magnetic ions is strong, and provides a possible mechanism to account for ferromagnetism. The surprising feature of the present observation is that it occurs in a salt which is magnetically highly dilute. The Bohr magneton value for the Cu^{++} ion is only 1·89, while if it has the same crystalline structure as magnetisum ammonium sulphate (the only Tutton salt which has been examined crystallographically), neighbouring Cu^{++} ions are separated by at least 6·1 A. Interaction effects between the ions should therefore be extremely small. One would expect that neither magnetic interaction nor exchange interaction would be important at temperatures above 0·1° K. Similar phenomena have in fact been detected at temperatures of this order of magnitude in other salts. Kurti, Lainé and Simon (1937) reported remanence in hydrated manganese ammonium sulphate at 0·1° K. and in iron alum at 0·017° K. Experiments in alternating magnetic fields (Cooke and Hull 1937, Shire and Barkla 1939, de Klerk, Steenland and Gorter 1949) have shown that heating effects, due to a component of magnetization out of phase with the field, occur at a higher temperature than that at which remanence is detectable. It appears that the onset of these phenomena is very gradual and that the effect most easily detectable is hysteresis. It is hoped that more light may be thrown on the problem now that similar phenomena have been detected in a more accessible temperature range. An investigation of copper caesium sulphate at its 'Curie point' by the method of microwave spectroscopy is in preparation. Thermal measurements to determine entropy changes might also be fruitful.

Clarendon Laboratory,
Oxford.
21st August 1950.

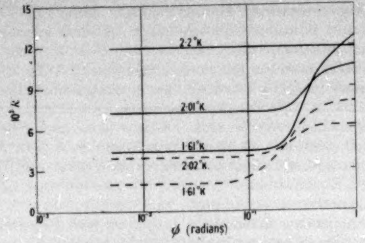
R. J. Benzie.
A. H. Cooke.

Benzie, R. J., and Cooke, A. H., 1949, *Nature, Lond.*, **164**, 837; 1950, *Proc. Phys. Soc.* A, **63**, 201.
Cooke, A. H., and Hull, R. A., 1937, *Proc. Roy. Soc.* A, **162**, 404.
de Haas, W. J., and Schultz, B. H., 1939, *Physica*, **6**, 481.
de Haas, W. J., Schultz, B. H., and Koolhaus, J., 1940, *Physica*, **7**, 57.
de Klerk, D., Steenland, M. J., and Gorter, C. J., 1949, *Physica*, **15**, 649.
Kurti, N., Lainé, P., Rollin, B. V., and Simon, F. E., 1936, *C. R. Acad. Sci., Paris*, **202**, 1576.
Kurti, N., Lainé, P., and Simon, F. E., 1937, *C. R. Acad. Sci., Paris*, **204**, 675.
Shire, E. S., and Barkla, H. M., 1939, *Proc. Camb. Phil. Soc.*, **35**, 327.

Oscillating Disc Experiments in Liquid Helium II

The viscosity, η_n, of the normal component of liquid helium II can be deduced from the damping of torsional oscillations of a system suspended in the liquid, since the superfluid component exerts no viscous force. For a system consisting of a pile of parallel discs suitably spaced, the normal component between the discs is also dragged into motion with the system and contributes a measurable moment of inertia, thus causing an increase of period from which the density ρ_n of the normal component can be determined (Andronikashvili 1946, 1948 b). For a system consisting of a single disc, however, the moment of inertia of the normal component carried with the disc is too small to be measured with sufficient precision to determine ρ_n separately and only the product $\eta_n\rho_n$ can be deduced (Keesom and MacWood 1938, Andronikashvili 1948 a). In all past experiments the amplitude of oscillation has been small, the logarithmic decrement has been independent of amplitude, and there is every indication that the Navier–Stokes equation, which is used to deduce η_n and ρ_n from the observed damping and period, holds for helium II. The present note reports preliminary results of experiments in which the effect of increasing the velocity of the oscillating system has been studied by increasing the amplitude and decreasing the period, in order to determine whether the Navier–Stokes equation still holds or breaks down in some way because of the increased importance of some frictional force such as that suggested by Gorter and Mellink (1949).

The periods and decrements of a number of systems have been measured in helium II at various temperatures for various amplitudes and it has been found that, if the initial amplitude ϕ_0 is less than about 0·1 radian, the logarithmic decrement is indeed independent of amplitude, but if ϕ_0 is increased to about 1 radian, the decay of amplitude is no longer exponential, although the period is still independent of amplitude. This is illustrated by the Figure which shows the relation between k, the slope of curves between $(\log\phi)/2\pi$ and n (the serial number of the swing), and ϕ, the amplitude of the swing, for a single disc (radius 1·52 cm. and moment of inertia 1·63 gm. cm^2). It can be seen that for temperatures below the lambda-point k begins to increase with ϕ at an amplitude of about 0·1 radian; the fact that this increase does not occur above the lambda-point indicates that the effect at lower temperatures must be associated in some way with the peculiar hydrodynamics of helium II. From the constant values of k at small amplitudes (which are just the logarithmic decrements) and for periods of about 4 and 11 sec. values of $\eta_n\rho_n$ have been deduced which agree with those of Andronikashvili (1948 a) but not with those of Keesom and MacWood (1938). This discrepancy, as has been pointed out by Landau and Khalatnikov (1949), is due to the erroneous correction used by Keesom and MacWood for the damping due to the edge of the disc. The curves of k against ϕ for piles of discs also begin to rise at about 0·1 radian, but show less flattening at the largest amplitudes. The values of η_n and ρ_n deduced from the small amplitude data for vacuum periods of about 3 and 12 sec. again agree with the results of Andronikashvili (1948 a, b).



Full curves for a period of 11 sec.
Dotted curves for a period of 4 sec.

It does not seem possible to explain the variation of k with ϕ by the assumption of turbulence in the normal component because the effects occur at Reynolds numbers as low as 20. It may be noted also that the peripheral velocity of the system corresponding to the amplitude at which k begins to increase is of the order of 10^{-1} cm. sec^{-1}, which is about 100 times less than the critical velocity associated with film flow. Moreover, from the fact that the period of oscillation is throughout independent of amplitude, it follows that the superfluid component is still not moving with the discs even at the largest velocities, so that the division of the liquid into two components still has significance. An order of magnitude calculation does, however, suggest that the variation of k with ϕ can be explained, at least in part, by the assumption of a mutual frictional force of the type suggested by Gorter and Mellink (1949), but some features connected with the variation of the effects with temperature and period are still obscure and experiments are continuing to clarify them.

Note added in proof. Further analysis of the data indicates that for a pile of discs the period *does* increase slightly with amplitude and suggests that at high velocities the superfluid does begin to move with the discs.

Royal Society Mond Laboratory,
University of Cambridge.
29th September 1950.

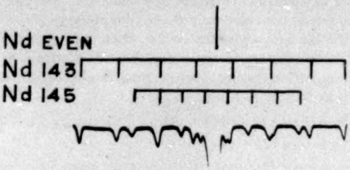
A. C. Hollis-Hallett.

Andronikashvili, E. L. 1946, *J. Phys. U.S.S.R.* **10,** 201; 1948 a, *J. Exp. Theor. Phys., U.S.S.R.*, **18,** 424; 1948 b, *Ibid.*, **18,** 429.
Gorter, C. J., and Mellink, J. H., 1949, *Physica*, **15,** 285.
Keesom, W. H., and MacWood, G. E., 1938, *Physica*, **5,** 745.
Landau, L. D., and Khalatnikov, I. M., 1949, *J. Exp. Theor. Phys., U.S.S.R.*, **19,** 637.

Nuclear Spins of Neodymium 143 and 145

The method of paramagnetic resonance has been applied to determine the nuclear spins of neodymium 143, 145 together with the ratio of their magnetic moments. It is found that the spin is 7/2 for both isotopes, and the ratio of the moments (143/145) is 1·61±0·01.

Of the salts of the rare earths, the ethyl sulphates are very suitable for this purpose since they form hexagonal crystals with two ions in unit cell whose magnetic behaviour is identical. Thus only a single spectrum is obtained. Bleaney and Ingram (1949) reported that neodymium ethyl sulphate showed an extensive hyperfine structure. This has been completely resolved by the use of a crystal diluted with lanthanum ethyl sulphate in the ratio Nd: La ≃ 1: 200. The line width at a temperature of 20° K. is about 15 gauss, and the spectrum consists of a single strong line flanked by sixteen satellites. The strong line is due to the even isotopes 142, 144, 146, 148 and 150 which have spin zero (a hyperfine structure of one-tenth of that of the smaller of the odd isotopes (145) would have been detectable). The sixteen satellites fall into two groups of eight (see Figure), the intensity of one group being approximately 1·5 times that of the other. Thus the groups are identified as belonging to the isotopes 143 and 145, whose abundances are 12·2% and 8·3% respectively (Inghram, Hess and Hayden 1948). The intensities relative to the strong line agree with these abundances within our experimental error. Since the hyperfine structure should consist of $\overline{(2I+1)}$ lines from each isotope, the spin is shown to be 7/2 in each case. The ratio of the magnetic moments is found from the ratio of the overall widths of the hyperfine groups. No effects could be detected which could be assigned to a nuclear electric quadrupole interaction.



The measurements show that the ground electronic state of the neodymium trivalent ion in this salt is a Kramers doublet whose spectroscopic splitting factor g is 3·58 parallel to the hexagonal axis and 2·09 perpendicular to it. If the hyperfine structure is described by the usual Hamiltonian

$$AS_zI_z+B(S_xI_x+S_yI_y)+Q\{I_z^2-\tfrac{1}{3}I(I+1)\}$$

the values of the constants are $A=0{\cdot}040$ cm^{-1}, $B=0{\cdot}020$ cm^{-1} for the isotope 143, and $A=0{\cdot}025$ cm^{-1}, $B=0{\cdot}012$ cm^{-1} for the isotope 145. Only an upper limit of 0·002 cm^{-1} can be assigned to Q for either isotope. In the present state of the theory, no estimate concerning the size of the nuclear magnetic moments can be made from these data.

Similar measurements have also been carried out on diluted gadolinium ethyl sulphate. The trivalent gadolinium ion is in an ^{8}S state, and seven electronic transitions are observed at temperatures of 290°, 90° and 20° K. The variation of the splitting with angle shows that terms with axial rather than cubic symmetry predominate, as in the case of the manganese salts investigated by Bleaney and Ingram (1950). No trace of any hyperfine structure is visible, though the intensity was adequate to detect any lines due to the odd isotopes (155, 157) whose separation from the main lines was more than 20 gauss. This shows that the gadolinium ion is in a fairly pure 4d^7 ^{8}S state, where the electrons have so nearly spherical symmetry that both magnetic and electric quadrupole splittings are practically zero. This behaviour is in contrast with that of the 3d^5 ^{6}S manganese ion, where a wide hyperfine structure is attributed to admixture of a state such as 3s 3p^6 3d^5 4s ^{6}S, which has an unpaired s-electron (Abragam 1950).

Clarendon Laboratory,
Oxford.
28th August 1950.

B. Bleaney.
H. E. D. Scovil.

Abragam, A., 1950, *Phys. Rev.*, **79**, 534.
Bleaney, B., and Ingram, D. J. E., 1949, *Nature, Lond.*, **164**, 116; 1950, *Proc. Roy. Soc.* A, in the press.
Inghram, M. G., Hess, D. C., and Hayden, R. J., 1948, *Phys. Rev.*, **74**, 98.

The Stresses and Energies associated with Inter-Crystalline Boundaries

In his paper on stresses and energies associated with inter-crystalline boundaries Dr. van der Merwe (1950) refers to some calculations which I made on the Fourier series for the interaction energy between two crystal lattices. In these calculations I computed the interaction energy between two hexagonal close packed planes; they are still unpublished and the reference given is therefore irrelevant. I have now calculated the interaction energy between two square lattice planes (the case he considers) and the results are given below.

Consider the boundary between two (100) planes of a body-centred cubic lattice where the atoms in the planes on either side of the boundary form a square lattice and the atoms of the upper plane lie above the centres of the squares in the lower plane. To estimate the relative magnitude of the various terms I have used a Lennard–Jones interaction $-a/r^6+b/r^{12}$ for the mutual potential of two atoms distance r apart. Further, since planes other than the two on either side of the boundary contribute less than 0·1% to the variation in the interaction energy, it is sufficient to consider only these two planes.

For simplicity, let the lattice parameter be 2π, then the ratio b/a is determined by the condition that the equilibrium separation between the two planes is π, as in the bulk crystal. When one plane is displaced from its equilibrium position by distances (x, y) along the sides of a square the interaction energy is found to be

$$\begin{aligned}&-[\cos x+\cos y]+0{\cdot}622[\cos(x+y)+\cos(x-y)]+0{\cdot}261[\cos 2x+\cos 2y]\\&\quad-0{\cdot}175[\cos(2x+y)+\cos(2x-y)+\cos(x+2y)+\cos(x-2y)]\\&\quad+0{\cdot}058[\cos 2(x+y)+\cos 2(x-y)]-0{\cdot}041[\cos 3x+\cos 3y]\\&\quad+0{\cdot}030[\cos(3x+y)+\cos(3x-y)+\cos(x+3y)+\cos(x-3y)]+\ldots,\qquad\ldots\ldots(1)\end{aligned}$$

apart from a constant numerical factor and an additive constant. The separation between the planes is constant throughout. For $y=0$ this gives (using more terms)

$$-0{\cdot}053\cos x+0{\cdot}0075\cos 2x-0{\cdot}0006\cos 3x,\qquad\ldots\ldots(2)$$

the coefficient of the last term being rather uncertain. Allowance for the change in separation (required by the condition of minimum energy) with relative displacement of the planes would reduce the coefficient of the second harmonic somewhat. The coefficients in these Fourier series are determined almost entirely by the repulsive potential, since it varies much more rapidly than the attractive potential. Furthermore, Fürth (1944) has shown that the potential $-a/r^4+b/r^7$ would be more appropriate for most metals. For such a potential the magnitudes of the coefficients in (1) would be smaller and they would decrease more rapidly to zero as the order of the harmonics increases.

For a set of equidistant edge dislocations parallel to the y-axis the displacements in this direction will always be zero. Thus, on differentiation of (2), it is clear that the force is well represented by the first two harmonics and that the second harmonic has an amplitude of 20–30% of the fundamental. The approximation made by neglecting the second harmonic therefore seems reasonable. However, because the coefficient of $[\cos(x+y)+\cos(x-y)]$ in (1) is so large, the approximation made by regarding two perpendicular sets of dislocations as independent and adding the energies associated with each set does not seem so reasonable. It is essentially the neglect of this term which leads to the result (in Part II of van der Merwe's paper) that the energy of a twist boundary is not a true maximum for an angle of twist of 45°.

In spite of both the above approximations, the argument in § 6 of the paper shows that the results will not be greatly in error when the density of dislocations in the boundary is small, i.e. a small degree of disorientation. On the other hand, the calculations are probably not very accurate for a large degree of disorientation. This view is supported by the experimental results of Aust and Chalmers (1950) which indicate that the interfacial energy flattens off rather sooner and more rapidly than is indicated by van der Merwe's calculations.

J. K. Mackenzie.

Commonwealth Scientific and Industrial Research Organization,
Division of Tribophysics,
Carlton, N.3, Victoria.

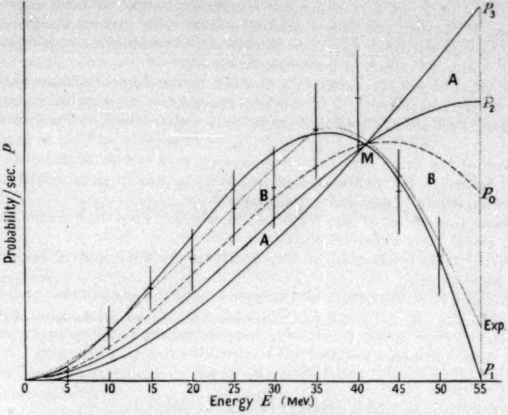
10th October 1950.

Aust, K. T., and Chalmers, B., 1950, *Proc. Roy. Soc.* A, **201,** 200.
Fürth, R., 1944, *Proc. Roy. Soc.* A, **183,** 87.
van der Merwe, J. H., 1950, *Proc. Phys. Soc.* A, **63,** 616.

Corrigendum

"Interaction between Four Half-Spin Particles and the Decay of the μ-Meson", by L. MICHEL (*Proc. Phys. Soc.* A, 1950, **63,** 514).

By an unfortunate oversight the curve P_0 in the diagram on page 529 has not been drawn correctly to scale. Since this figure may be useful for a comparison of experimental data with theory a correct drawing is given here.



The following minor corrections to the article may also be pointed out :

Page 525, 6th line from bottom, *insert* : "For Majorana particles" before "This symmetrization";

Page 528, in formula (45), 2nd line, first factor between brackets, *replace* the term "g_2^2" by "$4g_2^2$".

Obituary Notices

JAMES REGINALD ASHWORTH

The death of James Reginald Ashworth on 9th July 1950 deprived scientific circles in the north-west and farther afield of a highly esteemed member. At the age of eighty-nine, he had only recently resigned from the office of honorary secretary of the Rochdale Literary and Scientific Society after sixty-five years, and he had been a co-opted member of the Public Libraries, Art Gallery and Museum Committee of Rochdale for sixty-three years.

Dr. Ashworth built up a considerable reputation in the wider scientific world. He wrote eighteen books and pamphlets dealing mainly with various aspects of magnetism. In May 1939 he was invited to address a conference on magnetism organized at Strasbourg by the French Central Council of Scientific Research.

For many years he had been deeply interested in the subject of atmospheric pollution and its effect on the transmission of ultra-violet radiation. He installed a gauge on the roof of the Rochdale Technical School and made daily observations to the Smoke Abatement Society.

At the time of his death Dr. Ashworth was curator of the Manchester Literary and Philosophical Society. Up to the end of last year he was in good health, attending the Council meetings regularly and giving valuable advice.

He had been a member of the Physical Society for fifty-three years and was also a Fellow of the Royal Meteorological Society.

The following tribute was paid to Dr. Ashworth by the vicar of Rochdale (the Rev. G. E. N. Molesworth):—

> " He said he valued above all things integrity and truthfulness of heart and mind. So indeed his life has proved. We shall not see his like again and we shall be immeasurably the poorer for it. He has reached the end honourably with his finger on the pulse of passing events."

ALFRED JOSEPH BULL

Dr. Alfred Joseph Bull was an outstanding personality of our time. Few men have gained distinction and honour in such widely different spheres of thought and action as geology and the graphic arts.

He started his career as an analytical chemist and later joined the staff of Messrs. Lumière where he was one of the pioneers in colour photography. He continued research on colour vision at the Northampton Institute where he lectured on Optics. In 1903 he joined the staff of the School of Photo-engraving and Lithography at the old house in Bolt Court, once a residence of Dr. Johnson. Here with A. J. Newton, the Principal, he investigated the problems of colour photography in relation to photo-engraving, especially with regard to the sensitivity of photographic emulsions, the transmission of filters, and the testing of lenses for colour work.

In 1912 Bull became Principal of the new school built on the original site in Bolt Court. He approached his new responsibilities from a new angle. Research was not regarded as a proper activity for a technical school by the Education Authority of that time. Despite this, Bull concentrated on technical research to such a degree that it became the educational tradition of Bolt Court and helped to establish its international reputation. His own contribution from the year 1912 to the time of his retirement in 1946 was considerable. His special field was colour reproduction, and his work formed a foundation for much of the development of ' colour masking ' in recent years. Alone or in collaboration with his staff he published numerous papers on other aspects of photo-engraving including tone-rendering, densitometry, and ' pattern ' in colour reproduction.

In 1933 Bull was elected President of the Royal Photographic Society and continued in office to play a leading part in the Fox Talbot centenary the following year. During the last war he was concerned with research for the War Office, and Field Survey, and on techniques for the production of ' graticules '. The story of this work and of the establishment of munitions factories at Bolt Court and Putney has been told in a report he published at the end of the war and in a series of papers read at the Royal Photographic Society.

Bull's geological work covered a wide field including geomorphology, stratigraphy and tectonics. He became a member of the Geologists' Association in 1916, served on its Council for many periods, became President, 1926–38, and subsequently served as Vice-President and successively as Secretary of the Fields Meetings and Publications Committees. As Chairman of the Weald Research Committee from its inception he was active in carrying out an important part of the geological survey of the South Downs, the river valleys and the South Coast.

He was also a Fellow of the Geological Society and for some time Treasurer of the Mineralogical Society. As a result of several visits to the Alps with Swiss geologists he became interested in tectonics and contributed valuable papers on the theory of Mountain Building. In this work he carried out many interesting laboratory experiments, and his papers were usually illustrated with photographs he had taken in the field.

His personal friends will remember Bull as a cheerful and interesting companion, always happiest when pursuing his geological interests. In retirement he continued much of his committee work and he was following his geological studies with vigour up to the time of his death. He was a modest man seeking only to find the truth in all that he did. Nothing could have pleased him more than the knowledge that the work he had started in such diverse fields would be continued in the same spirit of sincerity. H. M. C.

FREDERICK CHARLES CLARKE

The death of Mr. F. C. Clarke, a Fellow of the Physical Society since 1911, occurred after a very short illness on 16th February at the age of 72. His death will be deeply regretted by many old friends.

He was a native of Plymouth, having a brilliant scholastic career as Foundation Scholar of the Plymouth Grammar School. From there he proceeded with a National Scholarship to the Royal College of Science in 1898 and gained the Associateship of the College in Physics, and the Honours Degree in Physics of the London University.

Clarke was deeply interested in the growing activities of the many large and well-equipped Technical Colleges, and he acquired unique teaching experience by holding appointments at the Birkbeck College, Chelsea Polytechnic, and as teacher of Mathematics and Physics at the West Ham Technical College, founding courses which were recognized for Internal Students of the London University. In this way Clarke gained exceptional experience in studying the requirements of students both for University work and for work in Technical and Applied Physics, and thereby qualified himself for his subsequent career.

The outbreak of the war 1914 to 1918 removed him temporarily for military duties, as he was an active member of the Corps of London Electrical Engineers, R.E.(T). He was actually in camp at Dover commanding a Searchlight Company at the outbreak of hostilities, with the rank of Captain R.E.(T), and subsequently assumed command of the Dover searchlights with the rank of Major throughout the war.

After the war he resumed his duties as Lecturer in Physics at West Ham until 1930, when he was appointed as the first Principal of the Rotherham College of Technology, a position he held until 1948. His capacity was so highly appreciated that his term of service was extended five years beyond the normal retiring age. During that time Clarke devoted all his energies to equipping laboratories, recruiting staff, contacting the employers of the great steel and other industries of the neighbourhood, and to the social life of the students of the College.

On his retirement many tributes were paid to the zeal with which he fulfilled his duties. The amazing growth of the College was stated as being undoubtedly due in no small way to his tremendous drive and to the intimate relations he held with his staff and students. The original staff of four increased to 42 full-time and 88 part-time teachers, and the number of students increased from 750 to over 3000. The courses included all branches of engineering, from the principles of management and administration to the duties of foremen and supervisors in local works. Students worked for University Degrees in electrical engineering and metallurgy, chemistry, physics and mathematics.

Clarke kept in close touch with all developments in Technical Education, both local and national. He was past-president of the Association of Teachers in Technical Institutions, and later a member of Council of the Association of Principals of Technical

Institutions. He was also a member of Council of the Sheffield Section of the Institute of Production Engineers, and of the Sheffield Subsection of the Institution of Electrical Engineers, of which he was an Associate Member.

Probably visits to the Physical Society Exhibitions gave him the most pleasure, for here he could meet old friends and watch the wonderful achievements of those, who unlike himself, could devote themselves to physics research : he was at heart a physicist.

After a bare eighteen months of retirement he undoubtedly paid the penalty of the strain of a very active life.

He leaves a widow, a son and a daughter.

W. S. T.

JAMES ARNOLD CROWTHER

THE sudden death of Professor J. A. Crowther on 25th March at the comparatively early age of 66 came as a great shock to his many friends, and is a severe loss to the Physical Society, of which he had been a distinguished member for nearly 23 years. Since his retirement in 1946 he had lived in Cornwall, and although for some time his health had not been good his zest for life remained, and to the last he was actively interested in literary, scientific and educational matters. When I last saw him in December 1949 there was no sign of any flagging of his spirits, and in a letter which he wrote to me a few days before he died he sounded characteristically cheerful and happy. Our deepest sympathy is due to his widow and his two sons in their time of sorrow.

James Arnold Crowther was born in Sheffield on 28th August 1883, and received his early education at the Royal Grammar School. From there he entered St. John's College, Cambridge, with an open Science Scholarship, and after gaining First Class Honours in both parts of the Natural Sciences Tripos he started work as a research student in the Cavendish Laboratory under J. J. Thomson. He held the Mackinnon Studentship of the Royal Society, and in due course became a Fellow of his College. Most of the investigations going on in the Cavendish at that time were connected with ionizing radiations, and so it came about that Crowther entered the field of x-rays and radioactivity, which was to become the chief scientific interest of his life, and to which he made a number of important contributions. Later he became a pioneer in the study of the effects of penetrating radiations on living cells, and may fairly be said to have laid the physical foundations of radio-biology.

Crowther early showed exceptional gifts as a teacher. His style was lucid and always interesting, whilst his understanding of human nature, combined with a keen sense of humour, enabled him to keep his audience alert and eager to hear what was coming next. After serving an apprenticeship as a demonstrator under Dr. G. F. C. Searle, he was put in charge of the electrical laboratory, and also gave stimulating lectures on Electricity and Magnetism to students working for Part I of the Natural Sciences Tripos. When the Cambridge Diploma in Radiology was started in 1919, Crowther was appointed to the new University Lectureship in Physics as applied to Medical Radiology, a position which he held for four years, and in which he did splendid service in teaching comparatively advanced physics to medical graduates whose previous knowledge of the subject was scanty, and whose interests were mainly clinical. He was particularly well qualified to do this as, during the 1914–18 war, he had worked in the x-ray department of a war-time hospital, and had helped to develop radiographic technique at a time when all the work was done by means of gas tubes, and only the most rudimentary forms of equipment were available.

In 1924 Crowther was appointed to the Chair of Physics in the University of Reading, where he threw himself energetically into the task of organizing the physics teaching and building up a school of research. He was the author of a number of successful books, of which the best known is his *Ions, Electrons and Ionizing Radiations*. This book has passed through many editions since it first appeared in 1919, and has probably been read by every honours student of physics throughout the Empire during the past 30 years. It was no small task to keep a work of this character up to date, for the issue of a new edition had to be followed almost immediately by preparation for the next. His *Manual of Physics*, also first published in 1919, still retains its popularity, whilst the *Handbook of Industrial Radiology*, of which he was editor, has passed through two editions in five years. In his earliest work, *Molecular Physics*, published in 1914, as much as in his later writings, he showed the same clarity of style and the same gifts for arousing interest that characterized his lectures. Little more than a year ago he gave a most successful broadcast on his old Professor, J. J. Thomson, for whom he had always a profound admiration and affection. This talk brought him letters of appreciation from many old Cavendish men who shared his deep regard for 'J. J.' Crowther had a very wide experience as an examiner, and was as much interested in the proper conduct of School and Higher Certificate examinations as in special honours B.Sc. work.

Crowther served on the Council of the British Institute of Radiology for a number of years, was President in 1936–37, and gave the Silvanus Thompson Memorial Lecture in 1937. In 1947 the Institute elected him to Honorary Membership, and he was also an Honorary Member of the Faculty of Radiologists. He was a Founder Member of the Institute of Physics, of which he was Honorary Secretary from 1932–46, Vice-President in 1948, and to which he gave devoted service. He did much to raise the status of physics as a profession, and during the second World War he served for two years as Vice-Chairman of the Parliamentary and Scientific Committee, which was concerned with the proper use of scientific manpower.

Crowther's married life was a very happy one, and he owed much to the loyalty and devotion of his wife. Those who were privileged to enter his home could not fail to be struck by the warmth and friendliness of its atmosphere. His conversation was always amusing, and he had a ready wit, but he was essentially a man of simple tastes, who enjoyed a game of tennis or golf, and was always ready in the evening to make up a four at bridge. He took pleasure in foreign travel and spent many happy holidays abroad with his wife and family touring Europe in his car. More recently he had formed the wish to visit New Zealand to see his son who is engaged in academic work there. He had some gifts as a singer, and when he attended the annual Cavendish Dinner he could always be relied upon to give a tuneful and spirited rendering of the special Cavendish songs, most of which were written by the late A. A. Robb. He was particularly fond of the Gilbert and Sullivan operas, which he knew almost by heart. He had complete gramophone records of many of them, and never tired of playing them over in the evenings, particularly if he had a sympathetic and appreciative audience. His early association with the Cavendish Laboratory, as well as his later work at the Institute of Physics, brought him into intimate contact with large numbers of physicists, who will always remember him as much for his human qualities and personal charm as for his notable scientific achievements. He had a great gift for friendship, and will be sadly missed by all who knew him. G. STEAD.

GEOFFREY E. F. FERTEL*

THE tragic death of Geoffrey Fertel on 19th January 1949 marked the end of a man of remarkable ingenuity and individuality, great integrity, and yet considerable diffidence.

He was born on 19th November 1913, and his father was organist at Bromley Parish Church. He was educated at Sevenoaks School, and later came to study physics at the Royal College of Science. Here his almost prodigious experimental ability developed to the full and, not content with the experiments provided in the degree course, he devised and carried through a great deal of practical work at his home, including even an absolute determination of the ohm and the construction of Geiger counters and the necessary auxiliary equipment. All this was done with materials and components costing at most a few shillings, obtained from the most diverse places. He was a rigid functionalist and, especially at this time, took a kind of inverted pride in the fact that the non-essential parts of his apparatus were never unnecessarily good. Although he devoted most of his energy to practical physics and took little part in games or any other social activities, his interests were by no means as narrow as one might have thought on first meeting him. One discovered after a time that he was enviably well read in literature, both prose and poetry, and something of an authority on wild plants. It was at this time too that his practical joking was at its maximum—he had several ways of producing loud explosions at unexpected times and places, and one lecturer may perhaps remember spending an embarrassing time trying to bring the slide lantern into operation, only to find at length that one of the carbons was insulated by a tightly fitting black paper tube.

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* This notice was unfortunately just too late for publication in the 1949 volume of the *Proceedings*.

After graduating he worked under Sir George Thomson on neutrons, much of his time being spent with a team working on a time-of-flight experiment. Shortly before the war he left London to take up a post at the University of Bristol, where he did some work with Professor C. F. Powell on the photographic plate technique of detecting nuclear particles, then still in an early stage of development. On the outbreak of war he joined a mobile group fitting up coastal radar stations, and shortly after went on a cruise to the Mediterranean on one of H.M. ships to carry out radar trials. On such a retiring and introspective person these turbulent experiences had a profound effect. For the rest of the war he worked in Admiralty laboratories on radar, first at Portsmouth, later at Nutbourne, and finally back at the Physics department of Bristol University, where an Admiralty team under R. W. Sutton was working on the development of new valves. He specialized in gas discharge devices for common aerial working, and it is probably in this field that his most important work was done. At the end of the war the valve group moved from Bristol, but he remained there, now back on the University staff, and spent some time teaching and applying his knowledge of radar technique to more academic problems.

He spent most week-ends exploring the countryside on foot or bicycle, and it was at Bristol that he developed an interest in caving and canoeing. He delighted in any sort of climbing, and had an alarming technique of proceeding upside down, feet first, which was particularly effective when applied to trees. He will be remembered affectionately by everyone in the Physics Department at Bristol for the Heath Robinson devices which he delighted in making for Christmas parties. One of the best of these was a cigarette-lighter of arresting proportions. Built on the stand of an old astronomical telescope, and having a large and crooked tree-trunk as a prominent part of its structure, it attained a height of seven or eight feet, and was set in operation by first winding up some heavy pieces of scrap iron to a considerable height. On pulling a lever these weights were released and drove a primitive dynamo, the output from which heated a small wire. In the meantime the cigarette, which had been inserted in an ornate holder made from an old curly brass candlestick, was brought into contact with the wire, and had applied to its other end a partial vacuum produced by means of a bicycle pump, also driven by the weights. The probability of successful operation of the lighter was about the same as that of the more conventional kind. Apart from diversions of this kind he was an excellent though unconventional mechanic, and throughout his career made most of his apparatus himself, usually with remarkable speed.

In 1948 he obtained leave of absence from Bristol University to join the team working on the cyclotron at Birmingham University, under Professor Oliphant. By this time he had lost much of his former reserve and made many new friends.

The precise nature of the accident which resulted in his electrocution can never be known, since he was by himself in the cyclotron pit at the time, but there is no doubt that he died instantly.

The amount of published work he has left hardly does justice to his creative ability. Technical discussion with him was never easy: his mind was always leaping ahead, or perhaps sideways, but always to fresh ground, and whether or not any definite conclusion had been reached at the end, there were always dozens of new ideas and original suggestions for overcoming practical difficulties. All who knew him will agree that his personality was unique, and the contribution he had to make to science, not only by his own work but by the energy and enthusiasm which he could inspire in others, can ill be spared.

D. F. GIBBS.

CYRIL OWEN GREEN

CYRIL OWEN GREEN was born on 24th November 1920 and was educated at Campbell Square School, Northampton. He next studied as an evening student at the Northampton College of Technology and after obtaining the Higher National Certificate in Electrical Engineering decided to study Physics. He entered University College, Nottingham, in October 1942 with a Foundation Scholarship. After a short course Green's war service was spent as an electrical officer in the Fleet Air Arm.

Green returned to Nottingham in 1945 and obtained First Class Honours in Physics in the London B.Sc. examination in July 1948. He then became a research student at

Manchester University, working on the properties of oxide-coated cathodes. Later, in 1949, he joined the cosmic-ray group directed by Professor P. M. S. Blackett. He completed a useful analysis of the problem of ionization measurements in the Wilson cloud-chamber.

Last autumn Green spent three months helping to erect a large electromagnet at the observatory on the Pic-du-Midi in the Pyrenees. In May 1950 he again went to the Pyrenees in order to install a Wilson cloud-chamber in the field of the magnet. On 11th May, Green, a colleague and three French workers at the observatory started to climb the Pic. They were travelling light, made good progress and were resting at 8,000 ft. when Green suddenly collapsed and died shortly afterwards. The other members of the party and the observatory staff rendered what help they could, but it was of no avail.

In this way a career of great promise was brought to an early end. Green made many friends who will remember his quiet unassuming manner and unselfish disposition. In 1948 Green married Miss Lorna Rumney.

N. DAVY.

HERMAN SHAW

THE sudden death of Dr. Herman Shaw, Director of the Science Museum, at his home at Barnes on 4th May 1950, came as a surprise and shock to his many friends in the Museums and scientific worlds and in particular to the Physical Society, of which he was Honorary Treasurer. His record as administrator, scientist and man of affairs was an impressive one, and his friendliness and accessibility had endeared him to a very wide circle of acquaintances.

He was born on 14th October 1891, the only son of the late Mr. G. H. Shaw of Huddersfield. He was educated at Bradford Grammar School, where he obtained a Governors' scholarship, and at the Imperial College of Science and Technology, which he entered as a Royal Scholar in 1911. In 1913 he won an Aeronautics Research Scholarship at this College. In the first World War he became a Lieutenant in the R.N.V.R. in 1915, a Flight Lieutenant in the R.N.A.S. in 1916, and a Captain in the R.A.F. in 1917.

Shaw entered the Science Museum in 1920, and for the remaining 30 years of his life his energies were devoted to the development and expansion of its collections and services, and to research in Applied Geophysics, in which subject he became a world authority.

His work in Geophysics began in 1921, when he and the late E. Lancaster-Jones obtained permission to make extensive laboratory tests on an Eötvös torsion balance which had just been acquired by the Museum. The tests were described in two papers published in the Physical Society's *Proceedings*, and proved so successful that they were soon extended to field experiments. These were carried out first at a site in Shropshire and then in 1925 at Hodbarrow, Cumberland, using a British-made torsion balance in the design of which Shaw and Lancaster-Jones played a leading part. The experiments, the first of their kind to be carried out in the British Isles, showed in a striking way that an underground rock structure—in this case a limestone 'dome'—could be located and delineated with the aid of the torsion balance.

In 1928 Shaw and Lancaster-Jones designed their 'gravity gradiometer', a form of torsion balance specially modified for field work in the measurement of gravity gradients, and much smaller, lighter and quicker in operation than the earlier Eötvös form of balance.

Shaw's interest in Applied Geophysics was by no means confined to the gravity method of prospecting, but soon grew to cover all its aspects, and he became recognized as one of the leading authorities on the subject, on which he published in all about 20 papers.

Concurrently with his geophysical work, most of which was carried out in his spare time, Shaw was very active in purely Museum work. The ten years following World War I was a busy period for the Museum, for they saw the completion and occupation of the new East Block, which was formally opened by H.M. King George V in 1928. Considerable expansion took place in the Science Collections, and in this development Shaw played his full part. He was also responsible to a large extent for the special exhibition on Applied Geophysics held at the Museum in 1931, and was co-author of the Museum Handbook on the subject published at this time.

He was made a Deputy Keeper in 1931 and in 1935 was promoted Keeper of the Department of Physics and Geophysics. In 1939 he was put in charge of A.R.P. arrangements at the Museum, and later took full charge of the arrangements for the evacuation to the country of the greater portion of the Collections. This work he carried out with great efficiency and thoroughness, and it was largely due to him that the Collections came through the Second World War with a minimum of damage or deterioration.

Soon after the outbreak of the War, the Director of the Museum, Col. E. E. B. Mackintosh, was called away for military duties, and in 1940 Shaw was made Acting Director. Col. Mackintosh later returned to the Museum, but on his retirement in November 1945, Shaw was appointed to succeed him as Director.

He resolved at once that the Museum should be opened again to the public at the earliest possible date, and applied himself energetically to the task. Partial re-opening took place as early as February 1946, and Shaw's policy received immediate justification by the fact that by the end of that year over 1¼ million visitors had already seen the limited collections then on view. Over the succeeding four years steady progress was made in rehabilitation, and at the time of his death the work was nearing completion, although somewhat restricted in total extent by the loss of the Old Building through age and war damage.

In spite of the burden imposed by this work, Shaw found time to play a notable part in many outside activities. His association with the Physical Society in particular was a long and intimate one. He was elected a Fellow in 1914, and was a member of Council from 1935 to 1939 and from 1941 to 1946, in which year he was elected Honorary Treasurer, a position which he held at the time of his death. He was also a member of the Colour and the Optical Groups. He was a Founder Fellow of the Institute of Physics.

At the time of his death Shaw was also President of the Museums Association, a trustee of the Imperial War Museum, a governor of the Imperial College of Science and Technology and a manager of the Royal Institution.

Shaw married, in 1919, Constance, the daughter of Mr. F. Shaw of Harrow. They had one son, who died as a young man in 1946, after an illness involving much suffering near its close. The loss was a severe blow to Shaw and his wife, but he bore it with fortitude, and only those in close contact with him were able occasionally to realize what it had cost him.

Amid such an active life, Shaw left himself little time for hobbies. He was, however, proud of his garden, and took considerable pleasure in motoring.

As a man, his most notable characteristics were his energy and approachability. He never spared himself in work, but obviously enjoyed the wide range of contacts which it brought him. As Director he was just, firm and kindly, and showed a practical interest in the well-being of all his staff. His sudden death at the height of his powers is a severe blow to the Museum to which he devoted so much of his energy and talents, and will be widely regretted among his large circle of acquaintances in many walks of life.

F. A. B. W.

GEORGE WILLIAM TODD

George W. Todd, Professor of Experimental Physics in King's College, Newcastle-upon-Tyne, died on 24th February 1950, a few weeks after an operation. His health had been causing his friends anxiety for many months, but he had carried on with his work, although with growing difficulty, until the end of the previous term.

He was born in Birmingham in 1886 and, after attending a secondary school in that city, entered the University in 1904, where he studied under Poynting and graduated with Honours in 1907. After two years' research at Birmingham he was elected to an 1851 Exhibition, which he held at the Cavendish Laboratory under Sir J. J. Thomson. This was extended beyond the normal period of two years, until 1912, when he took up a science mastership at the Wattville Road School in Birmingham. In the following year he was awarded the D.Sc., and was appointed to the Royal Grammar School, Newcastle-upon-Tyne, as Physics Master. Here he remained until 1916, when the joined the Munitions Inventions Department of the Ministry of Munitions, later becoming head of the Physics Section. At the end of the war he was appointed to the newly established Chair of Experimental Physics at Armstrong College, Newcastle, where he remained until his death.

His research work was mainly experimental and covered a wide field. It was characterized throughout by elegance, accuracy and thoroughness, for he possessed in full measure the true physicist's appreciation of the aesthetic aspect of his subject. These qualities were first shown in his 1909 paper on the thermal conductivity of air and other gases, and they were equally apparent in his 1928 paper on an cxpansion method of measuring the Peltier Coefficient. His sojourn at the Cavendish Laboratory led to the publication of four papers on ionic mobilities, and provided him with a fund of pleasant reminiscence from which both he and his friends derived much enjoyment. It was evidently the most stiumlating and satisfying period of his scientific career.

His scientific work during the 1914–18 war was on quite different lines, being mainly concerned with gas reaction velocities, and on this subject he published in all some six papers. The most important of these was probably that in which, in collaboration with S. P. Owen, he derived expressions for the temperature coefficients of the velocity and equilibrium constants of homogeneous gas reactions. A little later he showed that physical equilibrium could be treated in a similar manner, and so obtained a vapour pressure equation which gave good agreement with experiment over a wide range of temperature. In the same year (1920) he published the results of some work on the rate of flow of gases through capillary tubes, from which he attempted, with a considerable measure of success, to establish a formula which should be applicable down to the lowest pressures.

At the time of his appointment to Armstrong College, and for some years later, research facilities in the Physics Department were very meagre and the teaching duties heavy. He published several further papers, and prepared a new and revised edition of Poynting and Thomson's *Properties of Matter*, but devoted himself mainly to lecturing, both inside and outside the College. In this he was most successful, having the gift of clear and simple exposition and a sympathetic appreciation of the difficulties of even the least intelligent of his audience. These attributes, together with his kindly and genial attitude to his students, earned him their esteem and affection, and his death was keenly felt by them. His colleagues also held him in the highest regard, for his sincerity, good-nature and unselfishness were patent to all. During the second war, when half the staff, including myself, were away, he took charge of the department and shouldered a very heavy burden of teaching and administrative work for nearly six years. This was entirely typical of him. He never sought responsibility, but was always ready to take on extra work for the benefit of others.

His main interests outside physics were gardening and painting. He was for many years a member of the Newcastle Society of Artists, and for the last few years of his life its Chairman. He was a Founder Fellow of the Institute of Physics, a member of the Faraday Society, a Fellow of the Physical Society since 1922, and Editor of the Durham University Philosophical Society's *Proceedings* since 1921. He gave numerous extra-mural courses and lectures, which were invariably well attended, and served as a member of the Investigating Panel for Higher Certificate Examinations in 1924–6, and again in 1937–8.

He will be remembered not only as a physicist who made many and diverse contributions to knowledge and as an unusually gifted expositor of his subject, but also as a man of most kindly and lovable nature. He will be sadly missed by his innumerable friends.

W. E. CURTIS

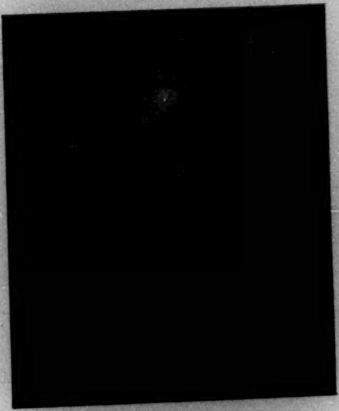
ALEXANDER WOOD

THE late Alexander Wood, M.A., D.Sc., Fellow and Tutor of Emmanuel College and Lecturer in Experimental Physics in the University of Cambridge: "I have no specialist's contribution to make. My rôle has always been that of interpreter rather than the research worker, and I only take courage from the fact that never was the rôle of interpreter more essential than in our own time." Thus Wood spoke of himself in his inaugural address to the Acoustics Group of the Physical Society (March 1947). He modestly left it there. But there is something more to be said.

Why with his intelligence and force was he, in these times, an academic scientist only? He was born in 1879 and died in 1950. He came to Cambridge from Lord Kelvin's degree lectures at Glasgow University just at the right time. He had the passion for enquiry. He was vitally interested in the scientific arena and was historian of the Cavendish Laboratory, yet in research had no contribution to make. I believe he deliberately left the laboratory, that he left it because, though enquiry was great, there was in fact something greater, and that his significance lies in the fact that in the considerable stress of our times he would not give up either orthodox Christianity on the one hand nor modern science on the other. Of course there is nothing surprising that he was also religious. In all periods there have been acute scientists who have seen nothing contrary to good sense in associating a Creation with a Creator and who would turn from sense data *in simplici intuitu*. But with Wood there was (in my opinion) a distinguishable factor. He was of the blood and the temper of the Scottish Reformers. He had the instinct of the theologian to organize the whole of knowledge, and felt that one half—Creation—is ultimately unintelligible without the other half. For him Truth was the aim and the battlefield, but Truth meant ' the Whole '. And it is natural that in his own historical period the battlefield must include the physical sciences because in that direction, in response to a profound gaze of man's faculties (what the mystics call a *quality of attention*), new knowledge and new power was emerging. He well knew the excitement of the chase—when detective plus inductive powers are in full cry—and always insisted that the creative faculties were as fully involved. But where was it leading, and into what theological pattern could it fit ? Once early in the thirties we discussed this in the Fellows' Garden at Emmanuel. The debate in Christian terms went somewhat thus : " Autonomous enquiry is inevitable—to know is a passion. But God permits scientists, endows them with infinite curiosity; then he permits ultimate risks; certainly, as part of the contingency of free-will and a cosmic design not fool-proof. What then becomes of the Kingdom of God on earth ? Here is the dialectic of Christianity : on the one hand the City of God, the reformer's inspiration, on the other the eschatology of the New Testament, the facing of catastrophe; religion is the technique of being at home on the edge of the precipice. It is for this reason that Christianity is so distasteful to Reason but so true as an account of Life itself." But Wood did not agree. When the deeps opened under him in the course of argument he had a peculiar metaphysical smile known to his friends—a smile of exhilaration. No, Christian Truth must include cosmic Truth. He meditated much on the Gospels and was Our Lord before Pilate—" For this cause came I into the world, that I should bear witness to the truth ". Wood writes : " The induction upon which we are called upon to act is not merely that the good life is the life lived and taught by Jesus : it is the whole view of God and the world from which his life issued and in virtue of which the life was and is possible." In his later years, as nuclear physics developed, the conviction of an all-in Christian Truth was not easy. Deeply anxious, he would look out over his peaceful Broads, or scan the rows of new Cambridge houses which, as councillor and chairman, he had done so much to build, and the words ' radioactive mud ' would frame themselves. Yet he did not despair. There was always something to be done in the immediate battlefield. He could preach, argue, defend his religion, " but first he followed it himself ". His action came out of his inner life. So he allowed himself to be many-sided, yielding to the service of God now here, now there. Like many pacifists, he was a bonny fighter, and in committee was a master of the tactical battle. The range of his activities was astonishing. In addition to his duties as fellow and tutor of his college, and (later) as chairman of the Borough Housing Committee, there was also the Student Christian Union (he was a frequent speaker at Swanwick), the Peace Pledge Union, the United Nations Food Organisation, the Cambridge Divisional Labour Party, the Welfare of Youth Union, the Fellowship of Reconciliation, and many others besides.

But action was not merely an anodyne. It was the testing of theory : it was part of his experimental method. Science was always much more than enquiry. It was also the selecting of what to enquire into, and it was the organizing and unifying of our knowledge. " We are face to face with an amazing multiplicity and diversity of phenomena constituting our physical environment. If we are to live intelligently we must organize our past experience so as to make it readily available for meeting the circumstances of the moment and for providing for the needs of the future. In the earlier stages the results of past experience are accumulated instinctively as an unorganized background in our minds. Later we became conscious of the need for organization, and Science is the response to this very practical need." He then continues : ". . . . in a sense religion is also a response to a similar practical need. Man's experience is not confined to sense data. He has to live in a world which, on the face of it at least, is a moral and even a spiritual world as well. Just as successful living in the first of these worlds—or the first plane in the only world we know—involves a mastery of our material environment, so successful living in the world's wider aspects means mastery in the moral and spiritual realms also. There is no more reason for us to be the playthings of our moral environment than there is for us to be the sport of our

HERMAN SHAW



JOSEPH ALFRED BULL

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JAMES ARNOLD CROWTHER

physical environment." The test of both, then, is successful living. "We want to understand life. We want to discover the great induction which will relate and give meaning to all its complex and puzzling experiences." He points to the fact that in Science it is not, at any particular time, the fashionable 'verification' which truly convinces us of a theory; it is the fact that the theory over a long period has contributed to render phenomena intelligible. And if it does so all kinds of anomalies and contradictions are endured. "Newton's Law of Gravitation has been subjected to innumerable verifications. Yet it seems probable that gravitation is a property of space, and not, as Newton thought, of matter." The importance of 'verification' is, however, that it shall make intelligible our future experience also. "This also we may fairly demand of religion. Our lives ought to be a continuous verification. We must not only understand the situations which have arisen in our past experience; we must be equipped to meet new situations as they arise. This double criterion is undoubtedly our test of scientific truth, and I conceive it to be the *intellectual* test of religious truth as well." (Italics are his.)

Wood thus gives philosophical significance to 'successful action' in the total issue of theoretical knowledge, and he transfers it from Science to Religion. Hence the importance of his active life. He was, moreover, fully conscious of the metaphysical weakness of parallels drawn from sense data. He believed there was no such thing as a logical refutation of philosophical idealism. Our conviction of the reality of things arises from constantly living among them and acting as if they were real. But if we direct our attention to, if we gaze at, material things only, their sense of reality grows because our powers of concentration are almost demonic in their summoning power. But by the same test spiritual things ignored lose their sense of reality. "In a world where the things of sense and time press on us more continuously and more aggressively than ever before, the reality of the unseen can only remain an unshakable conviction if we allow it to make its own impact upon us, and that means a scrupulous anxiety to preserve times and seasons when alone, or in fellowship, we may have leisure for worship and meditation and prayer. All these times must be opportunities for the unseen to make its own impact, and not times devoted to a fussy activity of our own. They must include spaces of silence in which God can speak to us. As we enter the doorway of religion it is simplicity that matters most. If we happen to be scientists or theologians we must not be disloyal to the spirit and temper and results of our scholarship, but neither must be wait outside in the vain hope that all our difficulties will be resolved."

The bulk of the quotations given above are taken from his book *In Pursuit of Truth—A Comparative Study in Science and Religion* (S.C.M. Press, 1927) and from *Some Implications of Modern Physics* (Independent Press Ltd., 1936).

H. BAGENAL.

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ABSTRACTS FOR SECTION B

Quelques recherches sur les raies faibles dans les spectres optiques, by P. Jacquinot.

ABSTRACT. En plus de la faiblesse absolue des raies, c'est surtout leur faiblesse relative qui interdit leur observation lorsqu'elles sont trop voisines d'autres raies. Elles sont alors masquées par la lumière provenant de l'étalement des raies voisines, qui est dû essentiellement à la diffraction dans le spectrographe.

Il est souvent possible d'observer les raies faibles en modifiant dans la source elle-même les rapports d'intensité entre les différentes raies, grâce au phénomène d'autoabsorption, dont quelques exemples d'utilisation sont donnés.

On peut aussi modifier profondément la figure de diffraction classique de façon à en atténuer les 'pieds'. Cette 'apodisation' est obtenue, soit par des diaphragmes de formes diverses, soit par des écrans absorbants dégradés suivant des lois convenables. Quelques indications sont données sur le calcul de ces lois, sur la réalisation des écrans, et sur les résultats obtenus, consistant en des améliorations de contraste au voisinage des raies, dans un rapport atteignant facilement 10 000.

Le plus interessant des résultats spectroscopiques obtenus jusqu'à présent est la mise en évidence et l'étude des raies d'intercombinaison de l'hélium. La plus facile à observer de ces raies se présente comme un satellite de la raie jaune, distant de 1 A., et 10 000 fois plus faible. Il a même été possible d'observer l'effet Zeeman de cette raie ; cet effet Zeeman est d'ailleurs différent de celui que l'on doit attendre, et cette contradiction pose un problème de rayonnement qui n'a pas reçu de solution.

Electron Microscopic Studies on Aqueous Sols, by M. R. A. Rao.

ABSTRACT. Electron micrographs are shown for aqueous sols containing the following colloidal suspensions: graphite, stearic acid, vanadium pentoxide, and sulphur. The results obtained explain certain divergences noticed during the measurement of depolarization of light scattering in these colloidal solutions.

Photoconductivity in Magnesium Antimonide Layers, by T. S. Moss.

ABSTRACT. Layers of Mg_3Sb_2 evaporated *in vacuo* are found to exhibit semiconducting properties, although both constituents are normally metals.

Under suitable conditions the layers are photosensitive. Measurements have been carried out on the spectral distribution of sensitivity, and show bands with long wavelength edges at $1{\cdot}5\,\mu$, $2{\cdot}6\,\mu$ and $3{\cdot}5\,\mu$. The former is identified with intrinsic conductivity, and the two latter with impurity levels.

Activation energies found from resistance–temperature measurements are very similar to the optical activation energies corresponding to the above wavelengths.

The Rehbinder Effect, by E. N. da C. Andrade, R. F. Y. Randall and M. J. Makin.

ABSTRACT. According to Rehbinder the immersion of wires of certain metals in non-polar paraffin containing a little oleic acid increases the rate of flow of the metal under a given stress and increases the electrical resistivity. The experiments described show that the mechanical effect can be obtained with single crystals of cadmium if the surface is contaminated by a thin oxide layer, which is known to increase the critical shear stress, but not if the surface is clean. The effect is accordingly attributed to the disruption of the hardening surface layer by the active agent and not to penetration into the metal, as assumed by Rehbinder. It has not been found possible to detect any electrical effects with cadmium or lead crystal wires having either clean or contaminated surfaces.

A Study of the Magneto-Resistance of Silicon–Iron, by R. Parker.

ABSTRACT. Iron containing a small percentage of silicon in solid solution has an unusually small magneto-resistance. Longitudinal and transverse curves of $\Delta\rho/\rho$ against field strength were obtained for a number of single and polycrystalline specimens. In large fields the curves show a linear decrease, which is less than 0·02 times that of nickel and cobalt in the corresponding field range. In small fields various unusual features are found. It is concluded that the small magneto-resistance of polycrystalline silicon–iron is due to the small contribution of individual crystallites and not to an averaging-out process.

Investigations on the Reversible Susceptibility of Ferromagnetics, by R. S. Tebble and W. D. Corner

ABSTRACT. A mutual inductometer bridge method has been developed to measure the reversible susceptibility κ_r of a ferromagnetic by the application of small alternating fields to specimens in the form of long wires. The corrections which must be applied because of the finite amplitude of the alternating field and for eddy current effects are investigated and an overall accuracy within about 1% is attained. Typical results are given for Swedish iron which show a marked increase in susceptibility after decarburizing and annealing, and this is discussed in relation to the ideas of Néel. By the evaluation of $\int\kappa_r\,dH$ over a suitable range of field, the minimum contribution of reversible processes to the total change in magnetization is estimated and found to vary from 10 to 20% for the specimens of iron and nickel examined. Finally an investigation has been made into the statement of Gans that reversible susceptibility is a unique function of intensity of magnetization and independent of the magnetic history of the specimen; the statement is shown to be true only for specimens which have been brought into a given state of magnetization round a hysteresis cycle, and then only for the regions of higher magnetization.

Congruent Space Charge Flow, by G. B. WALKER.

ABSTRACT. The paper is mainly concerned with one type of congruent flow, namely irrotational flow, and propositions are established regarding (*a*) rectilinear motion, (*b*) motion in which the current density is constant along lines of flow and (*c*) the representation of lines of flow by the level lines of a harmonic function. From the latter, three corollaries are deduced regarding flow in which the space charge density is constant either throughout the motion, or along lines of flow or along lines of constant action.

Two cases of curvilinear flow, originating from a unipotential cathode, are discussed and are shown to possess important features regarding magnification and transit time.

A 100-Kilowatt Water-cooled Solenoid, by J. M. DANIELS.

ABSTRACT. Design data and constructional details are given for a small water-cooled solenoid, which, for a consumption of 100 kw. produces a field of 14·7 kilogauss, uniform to within $\pm\frac{1}{2}\%$ in a cylindrical volume 6 cm. long and 4 cm. diameter. The solenoid contains no iron or other ferromagnetic material, and is in use at the Clarendon Laboratory, Oxford, for experiments on adiabatic demagnetization.

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